TECHNISCHE UNIVERSITÄT DRESDEN

DRESDEN concept

Concentrated Solar Radiation – An Option for Large Scale Renewable Fuel Production

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DLR

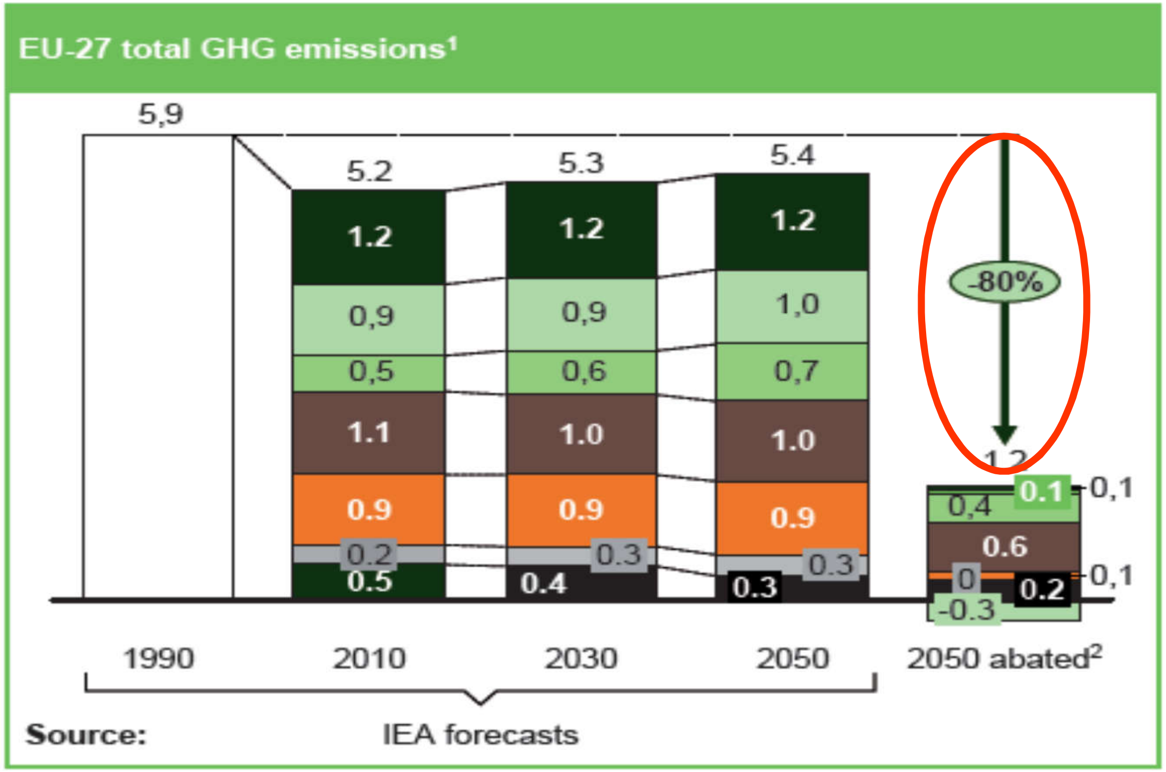
21st Conference of Parties - COP21
to the United Nations Framework Convention on Climate Change

- COP 1 Berlin 1995, COP 3 Kyoto 1997 – Kyoto Protocol,
  COP 22 Marrakech 2016, COP 23 Bonn 2017, COP 24 Katowice 2018
- 11th meeting of the Parties to the Kyoto Protocol (CMP11)
- Universal agreement by 195 parties (countries) to
  keep a global temperature rise this century well below 2 degrees Celsius
- and to drive efforts to limit the temperature increase even further to 1.5 degrees Celsius above pre-industrial levels.

21st Conference of Parties - COP21

- Additionally, the agreement aims to strengthen the ability to deal with the impacts of climate change
- **Appropriate financial flows will be put in place**, thus making stronger action by developing countries and the most vulnerable possible, in line with their own national objectives.
- The energy sector is responsible for some 60% of global emissions, making it a top priority for climate action.
- One country decided to withdraw which can formally happen earliest in 2020

Development of EU GHG emissions [Gt CO_2e]



Sector	Total abatement
Power	95-100%
Road transport	95%
Air & sea transport	50%
Industry[3]	40%
Buildings	95%
Waste	100%
Agriculture	20%
Forestry	-0.25 Gt CO_2e

1 Large efficiency improvements are already included in the baseline based on the International Energy Agency, World Energy Outlook 2009, especially for industry
2 Abatement estimates within sector based on Global GHG Cost Curve
3 CCS applied to 50% of large industry (cement, chemistry, iron and steel, petroleum and gas, not applied to other industries)

SOURCE: www.roadmap2050.eu

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Japan‘s Strategic Roadmap towards a hydrogen society

(Agency for Natural Resources and Energy, METI, 2014, revised March 2016, December 2017, October 2018)

Conveying to the world the information on the potential of hydrogen by taking advantage of the 2020 Summer Olympic Games in Tokyo

2020

2030

2040

Phase 1

2009: ENE-FARM DFC Program

2018: 270,000 DFC

Summer Olympic Games Tokyo

2020: 40,000 FCV

2030: 800,000 FCV

5,300,000 DFC

Fuel cell vehicles: Achieving a reduction of vehicle prices to the level of hybrid vehicles of the same class and price range

Phase 2

Full-fledged introduction of hydrogen power generation/
Establishment of a large-scale system for supplying hydrogen

Accelerating development and demonstration
Establishing a strategic partnership with hydrogen-suppliers overseas
Realizing inexpensive hydrogen , anticipating growth in demand

Around 2030:

H_2 price(CIF)

30 JPY/Nm^3 = 30ct/Nm^3

= \$ 3.25/kg

from unutilized energy resources imported from overseas

- Full-fledged introduction of hydrogen power generation for power-producing business

Phase 3

Establishment of a zero-carbon emission hydrogen supply system throughout the manufacturing process

Systematic development and demonstration of such a system, based on its potential for development

Japan sets the target to procure “CO_2-free” hydrogen in 2040 and looks for clean and cost competitive hydrogen globally.

DFC: Domestic Fuel Cell
FCV: Fuel Cell Vehicle
CIF : Cost, Insurance, Freight

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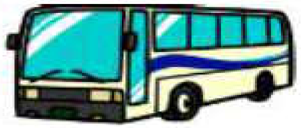
Annual Hydrogen Consumption (per unit)
(Source: METI, Japan)

FCV
94 kg/yr

(H_2-type)
residential FC
201 kg/yr



FC Bus
4,600 kg/yr

1GW H_2 power plant
(100% H_2 fuel)
200,000~400,000 ton/yr

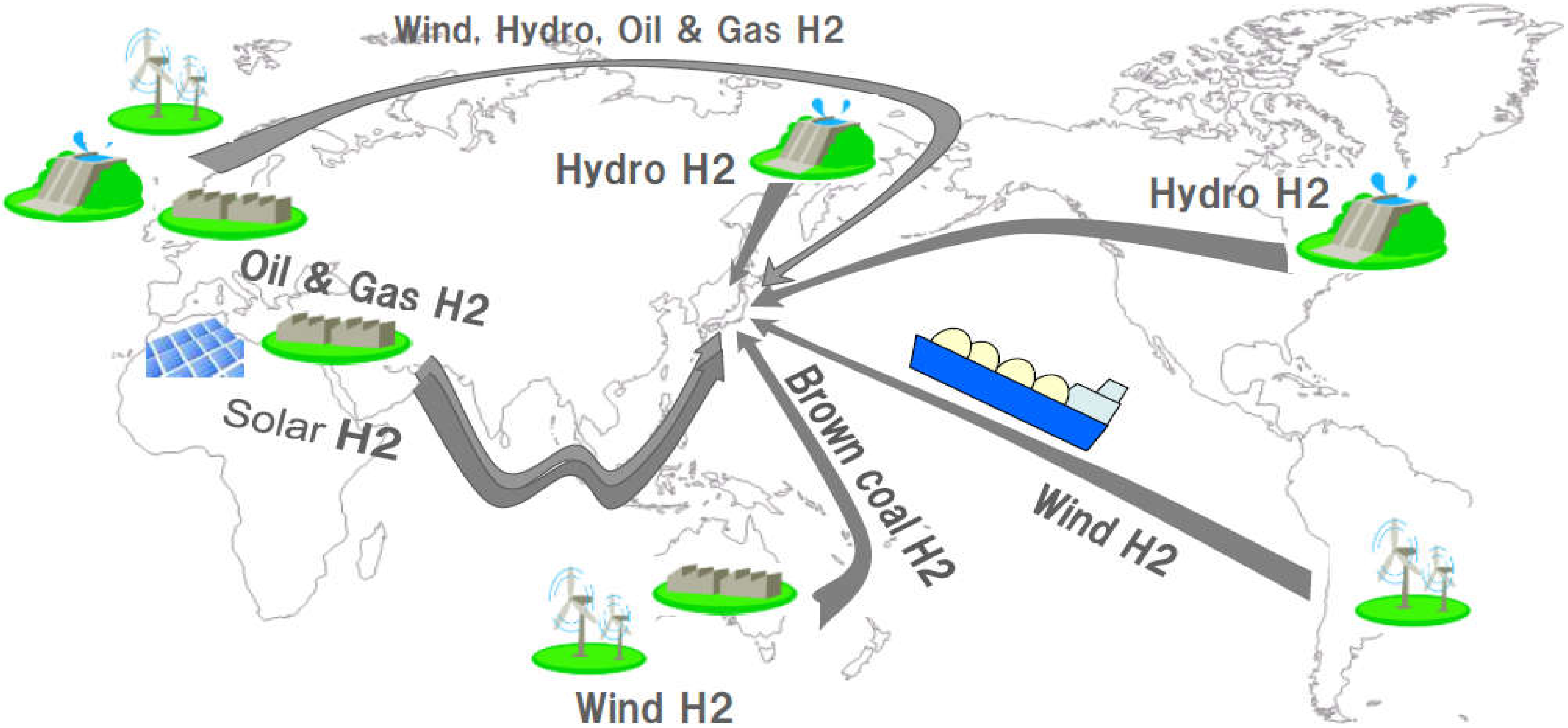
= 2~4 million FCVs

Japanese energy mix 2013: 303 GWe,

- 44 GWe nuclear, 45 GWe hydro,
- 36 GWe coal, 47 GWe gas,
- 41 GWe oil, 18 GWe oil or coal,
- 51 GWe autoproducers' 'combustible fuels' 13 GWe solar
- 2.6 GWe wind 0.5 GWe geothermal.

(Source: IEA, 2014)

Kawasaki Vision – Hydrogen Potential from Overseas



MISSION INNOVATION

MISSION INNOVATION

- Is a global initiative of **23 countries and the European Commission (for the EU)**
  - reinvigorate and accelerate global clean energy innovation
  - make clean energy widely affordable.
- MI was announced at COP21.
- Seek to **double governmental and/or state-directed clean energy clean energy research, development and demonstration (RD&D) investments over five years**.
- **Work closely with the private sector** as it increases its investment in the earlier-stage clean energy companies that emerge from government programs.
- Web-site: http://www.mission-innovation.net

Australia Austria Brazil Canada Chile China Denmark European Union Finland France Germany India

Indonesia Italy Japan Mexico Netherlands Norway Republic of Korea Saudi Arabia Sweden United Arab Emirates United Kingdom United States

Fourth Mission Innovation Ministerial gathering (MI-4), will take place in Vancouver, Canada on May 28th, 2019.

MISSION INNOVATION

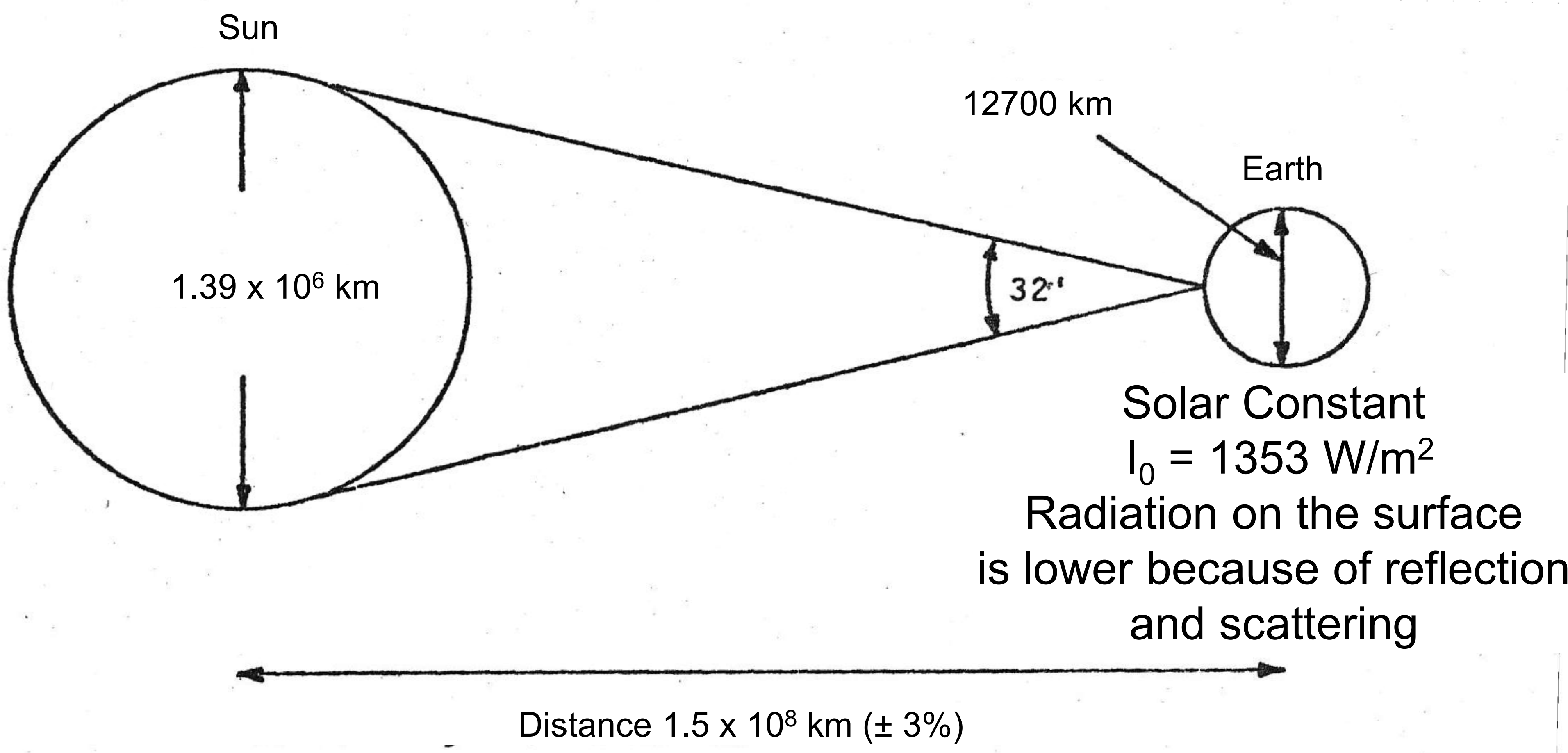
MISSION INNOVATION – Innovation Challenge 5: Converting Sunlight

Objective IC5: To discover affordable ways to convert sunlight into storable solar fuels.

Co-leads: European Commission, Germany

Participants: Australia, Brazil, Canada, Chile, China, Denmark, Finland, France, India, Italy, Japan, Mexico, Netherlands, Norway, Saudi Arabia, Sweden, UAE, UK, **USA**

Concentration is crucial for large scale solar fuel production
Solar energy is very diluted on Earth



Two concentration options: Power or Heat

HYSOLAR: PV + Alkaline Electrolyser
10 kW Demonstration, DLR Stuttgart, Germany 1990

HYDROSOL: Concentrated solar radiation + thermochemical cycle, 10 kW Demonstration
DLR Cologne, Germany 2005

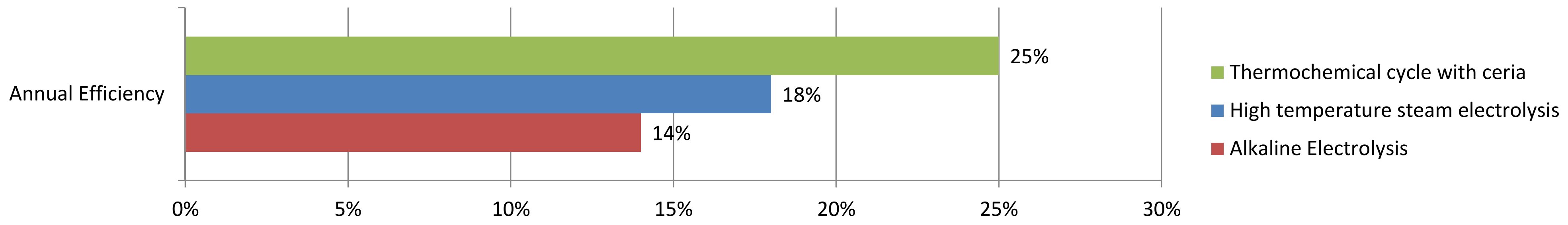
Technical Challenges – High temperatures and constant conditions
Promising and well researched Thermochemical Cycles

	Steps	Maximum Temperature (°C)	LHV Efficiency (%)
Sulphur Cycles			
Hybrid Sulphur (Westinghouse, ISPRA Mark 11)	2	900 (1150 without catalyst)	43
Sulphur Iodine (General Atomics, ISPRA Mark 16)	3	900 (1150 without catalyst)	38
Volatile Metal Oxide Cycles			
Zinc/Zinc Oxide	2	1800	45
Hybrid Cadmium		1600	42
Non-volatile Metal Oxide Cycles			
Iron Oxide	2	2200	42
Ceria	2	1800	68
Ferrites	2	1100 – 1800	43
Low-Temperature Cycles			
Hybrid Copper Chlorine	4	530	39

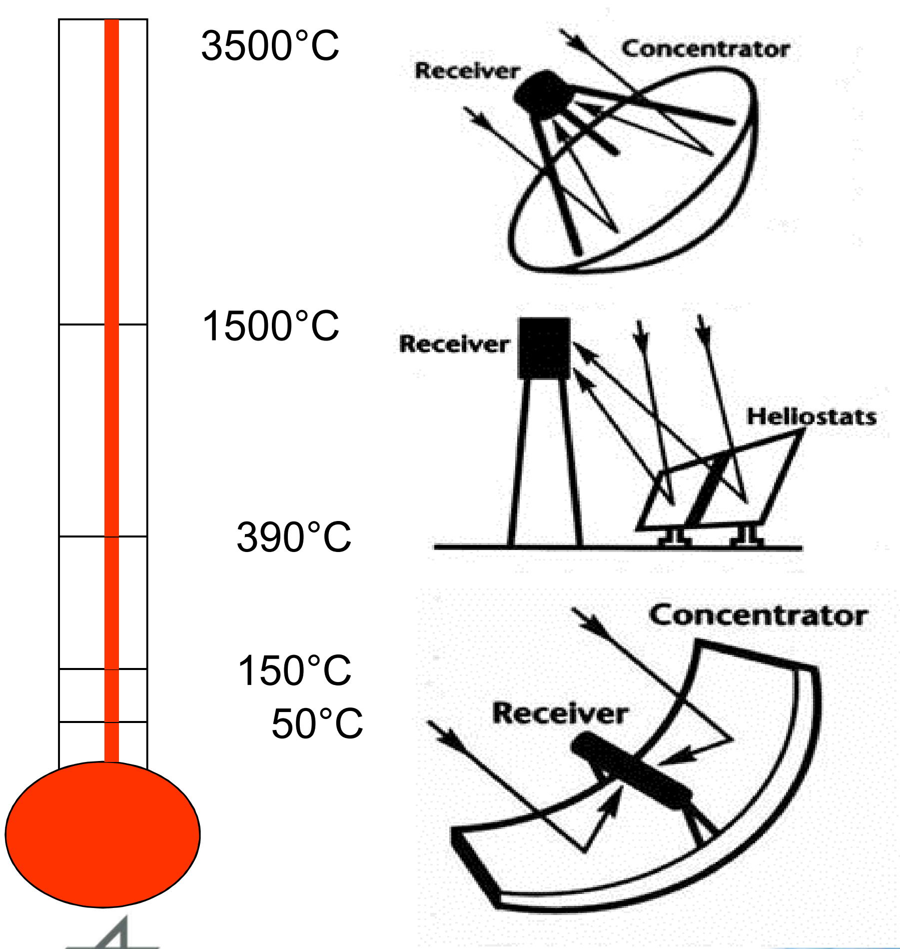
Solar Hydrogen by Thermochemical Water Splitting: Efficiency Comparison vs. Benchmark

Process	temperature of the chemical reaction	Solar interface receiver temperature
Alkaline Electrolysis	25°C	Solar PV
High temperature steam electrolysis	850°C	Future solar tower 1200°C
Thermochemical cycle with ceria	1500 / 1150°C	Future solar dish 1500°C

*G.J. Kolb, R.B. Diver SAND 2008-1900 / N. Siegel et al. I&EC Research May 2013



Temperature Levels of Solar Concentrators

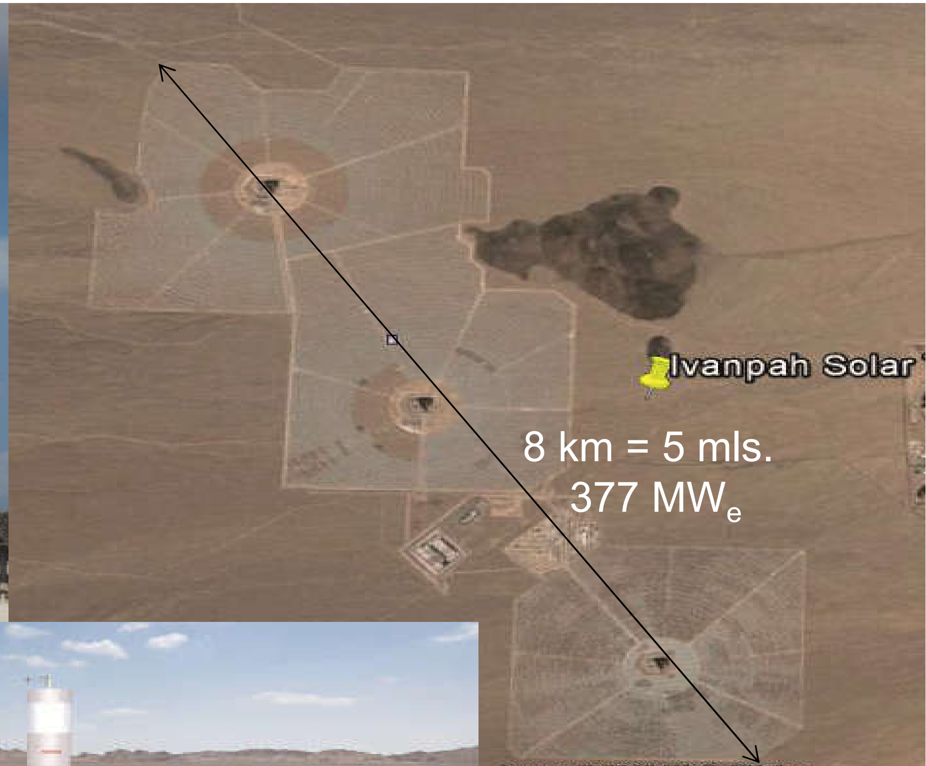


Paraboloid „Dish“
Concentration < 10.000
Power < 500 kW_{th}

Solar Tower
(Central Receiver System)
Concentration >100
Power >100 MW_{th}

Parabolic Trough /
Linear Fresnel
Concentration 10 - 100
Power 10 - >100 MW_{th}

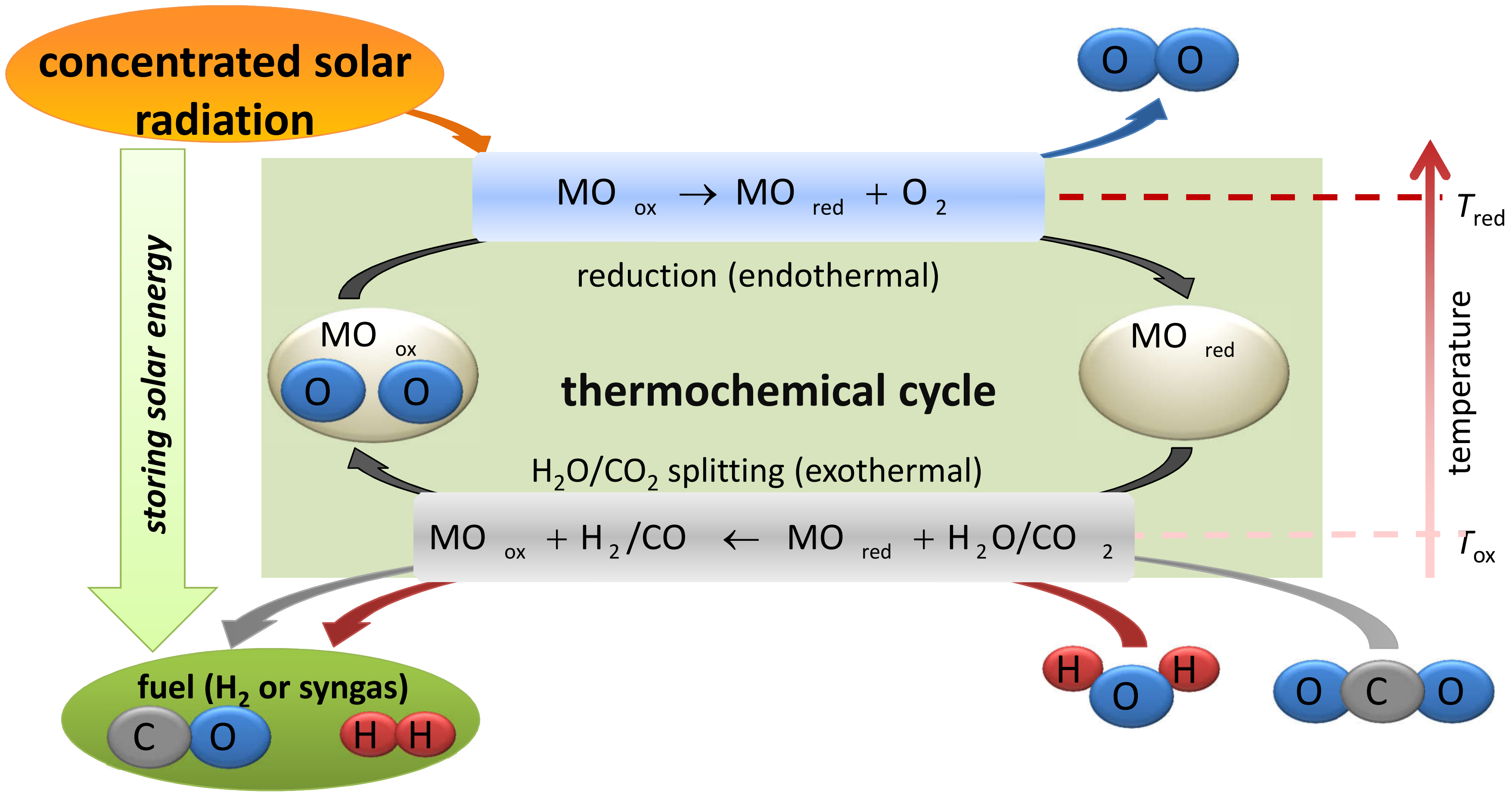
Solar Towers



On the Web:

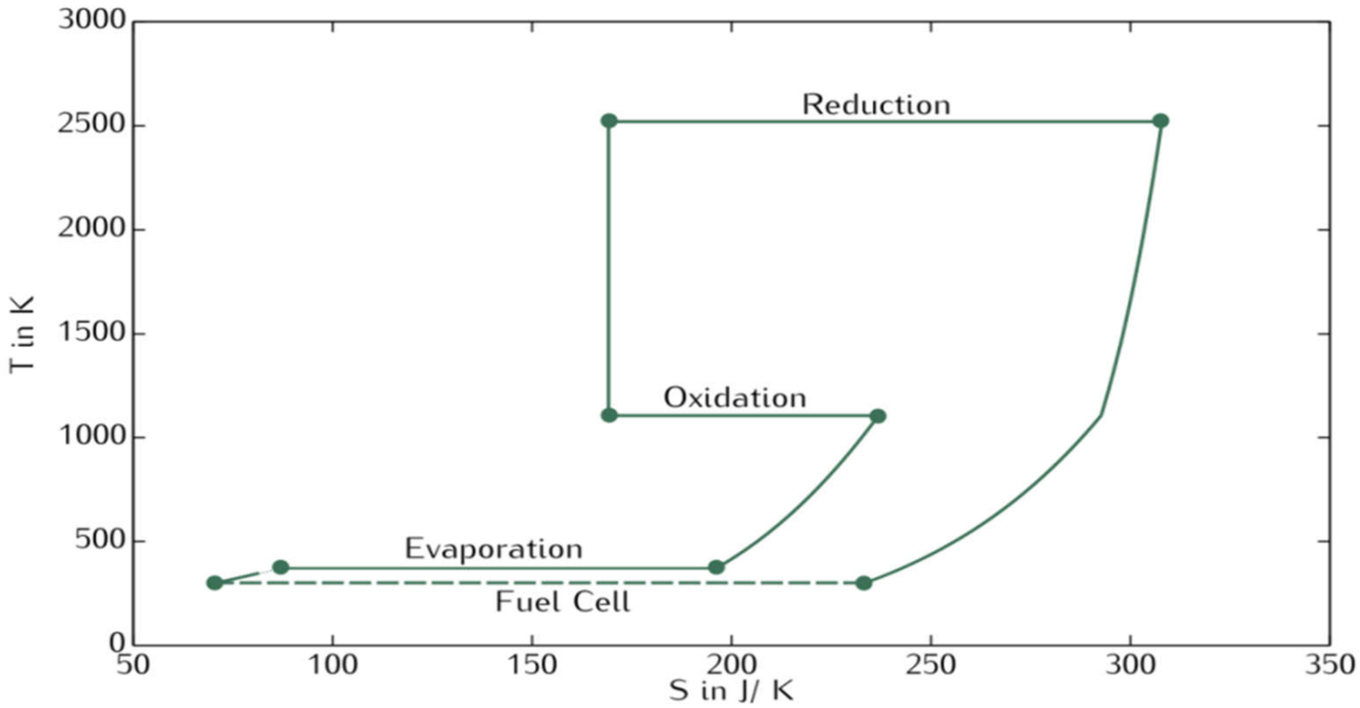
http://www.ivanpahsolar.com/
http://www.torresolenergy.com/TORRESOL/home/en
http://www.solarreserve.com/en/global-projects/csp/crescent-dunes
http://www.abengoasolar.com/web/en/

Thermochemical Cycles



T-S Diagram of the 2-stage thermochemical Water Splitting cycle

- Thermodynamic analysis of the Entropy change in the gas phase
- The integral under the curve equals the Gibbs-Energy of the reaction of 1 Mol hydrogen with oxygen.
- If the oxygen partial pressure is reduced during the reaction the area is shifted from top to right, as the reduction temperature is reduced

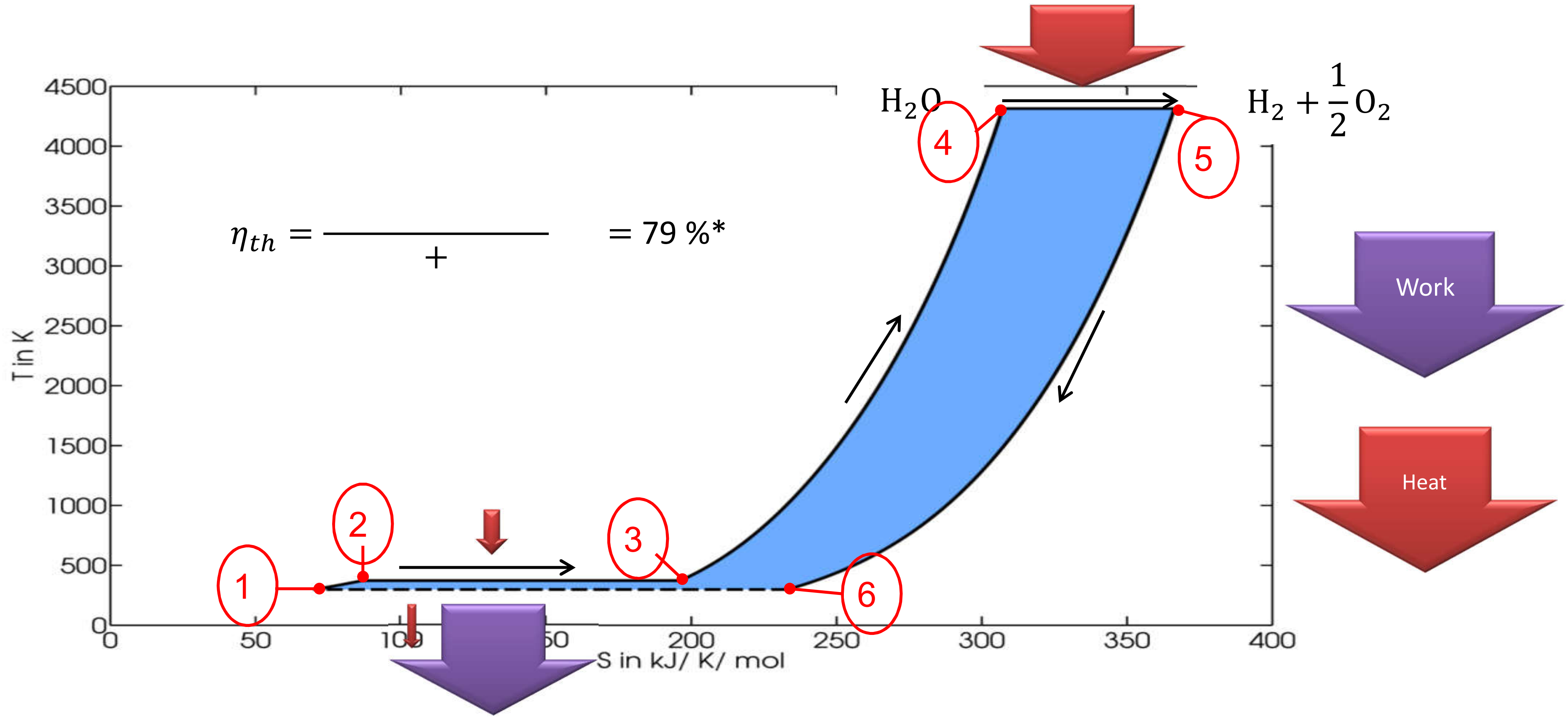


M. Lange, M. Roeb, C. Sattler, R. Pitz-Paal (2014) Energy, 67, 298-308. DOI: 10.1016/j.energy.2014.01.112

Direct Water Splitting T–S Diagram

$$\Delta G = \Delta H - T\Delta S$$

$$dQ_{rev} = \mathrm{T}\, dS$$

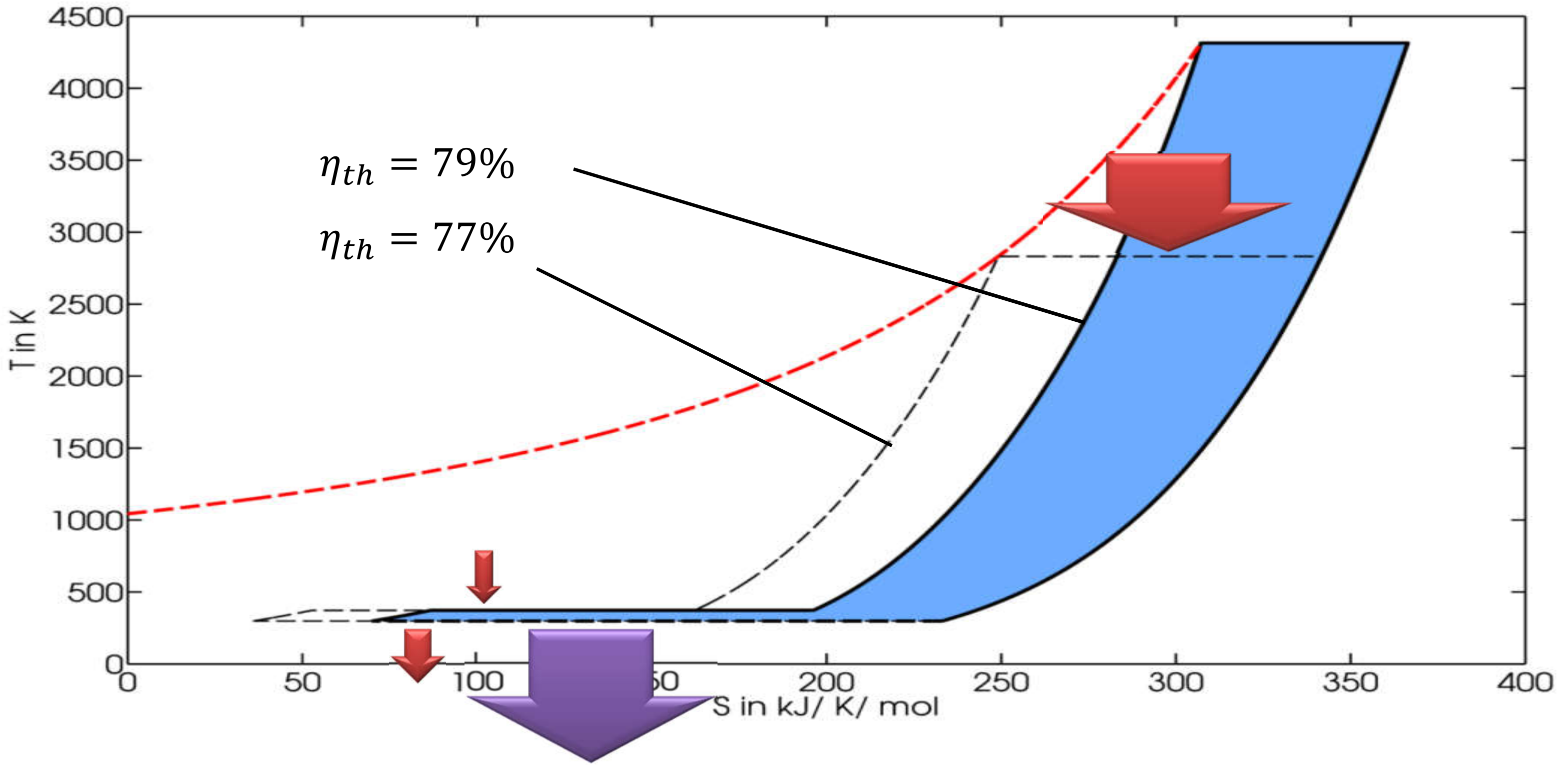


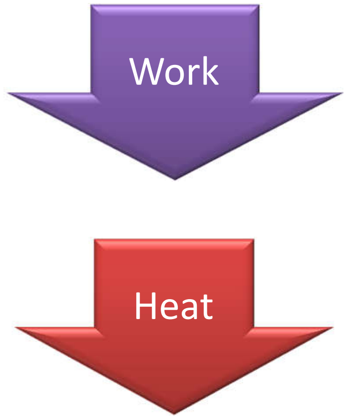
* Inclusive ideal heat recovery

Direct Water splitting: Equivalent Process

$$\Delta G = \Delta H - T\Delta S$$

$$dQ_{rev} = \mathrm{T}\, dS$$

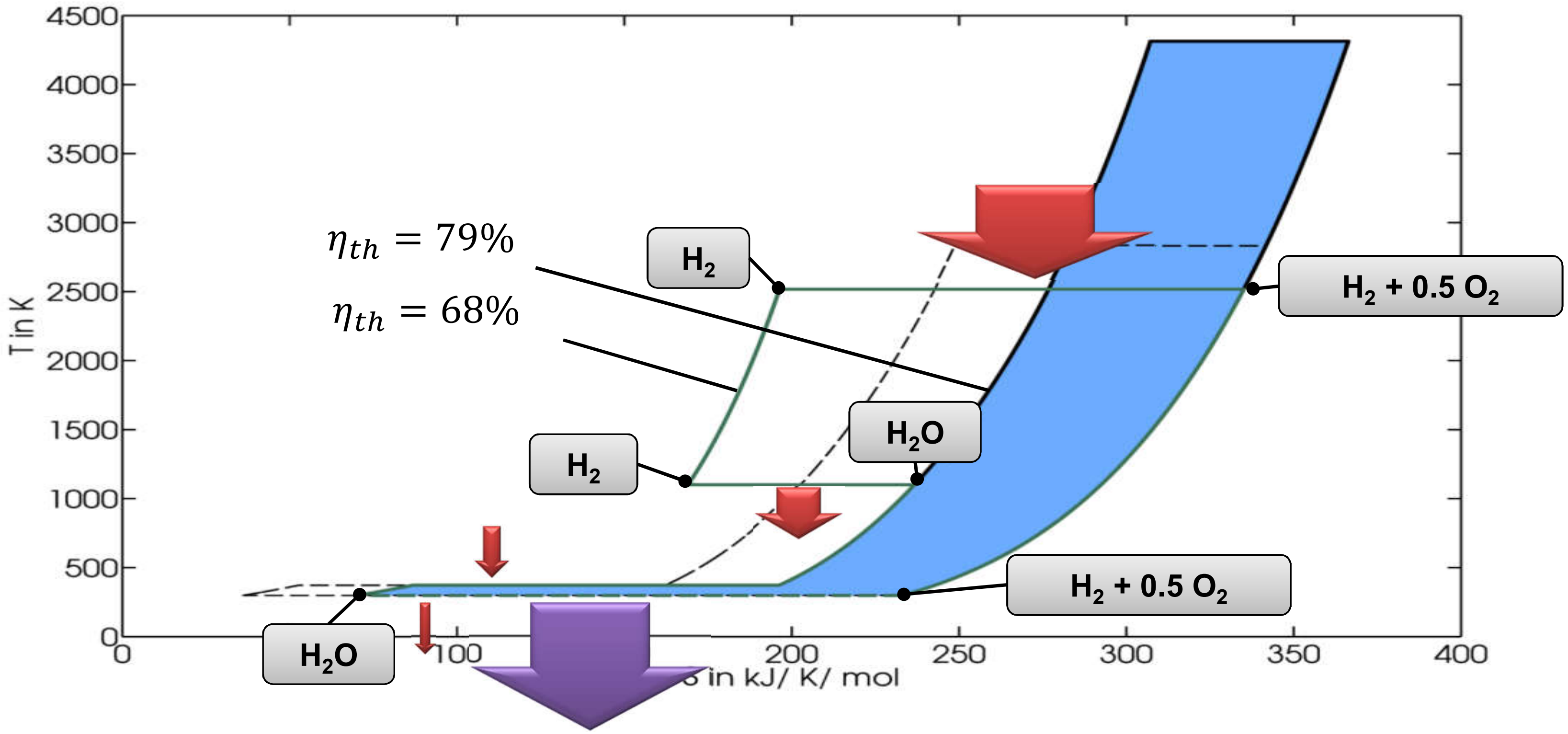




Two Stage Gas Phase Process

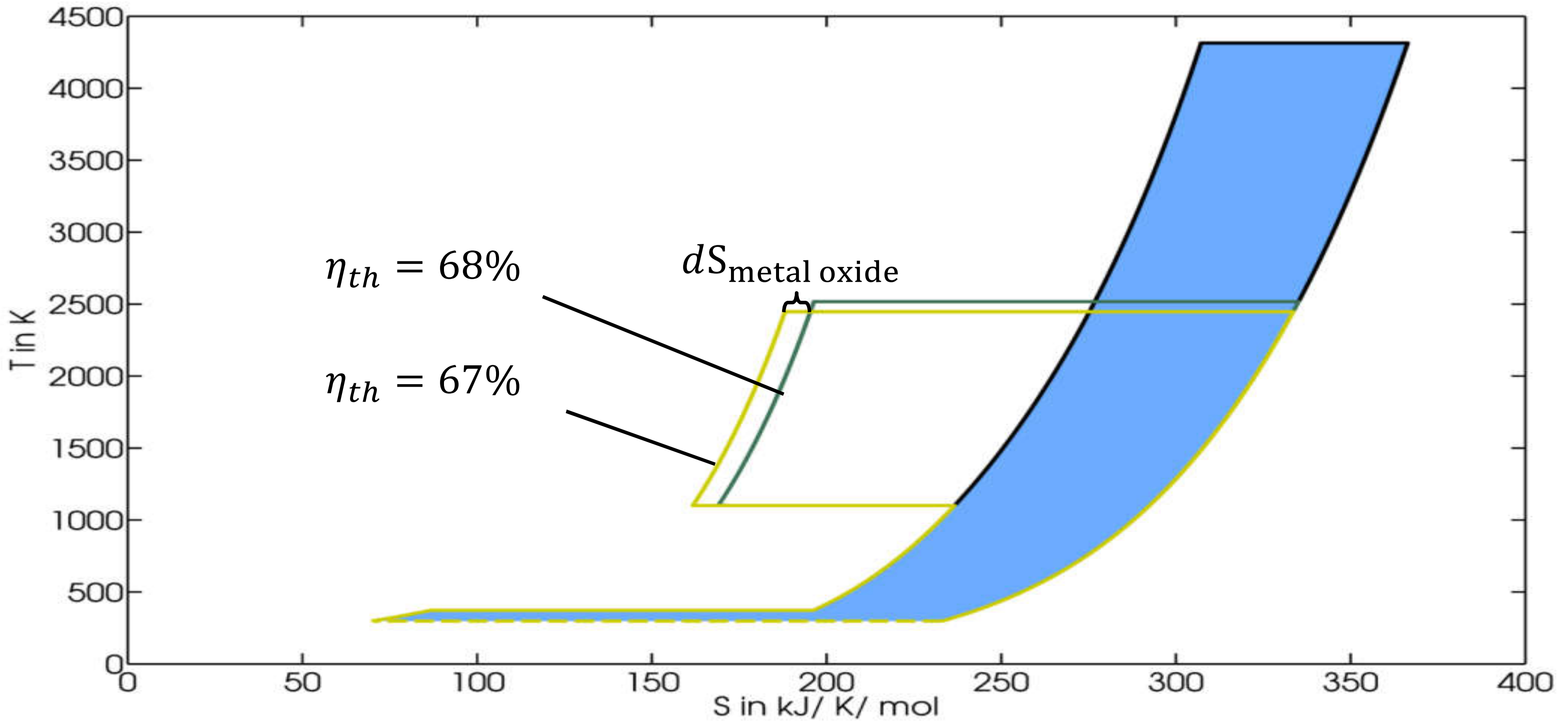
$$\Delta G = \Delta H - T\Delta S$$

$$dQ_{rev} = \mathrm{T}\, dS$$



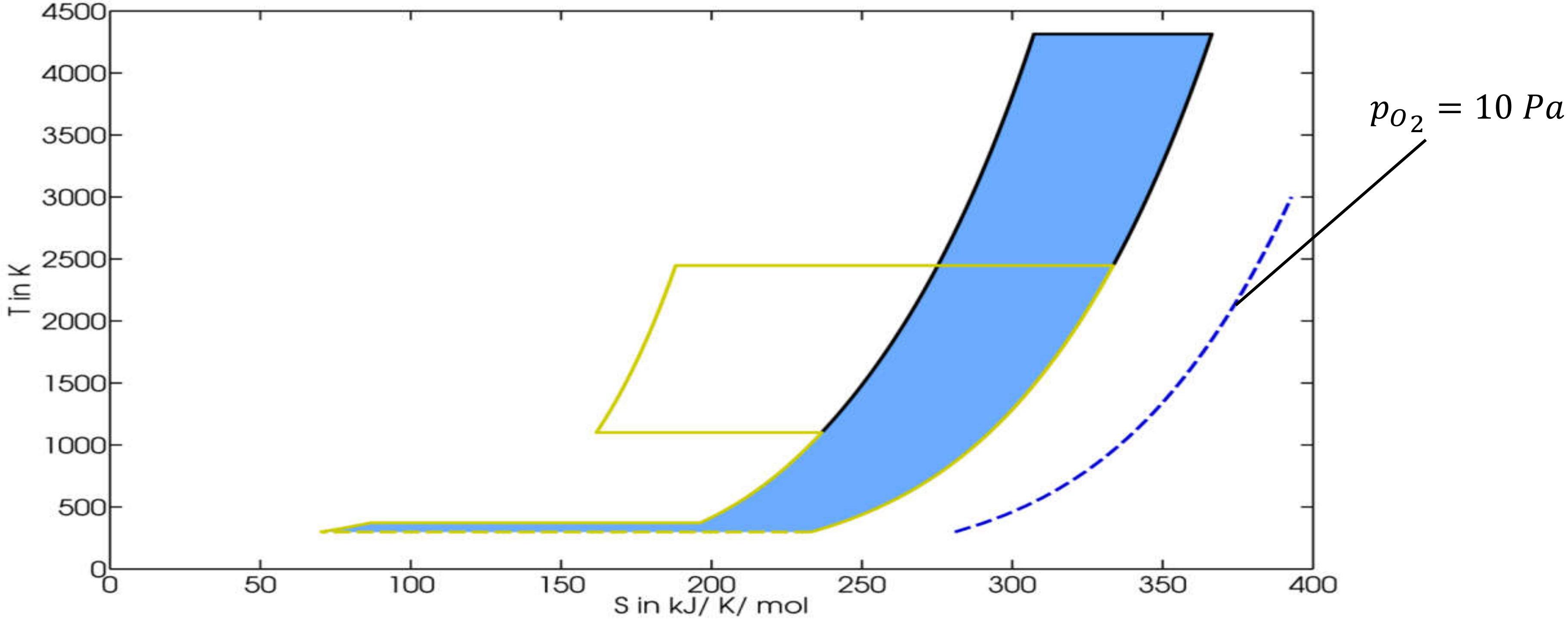
Two Stage Process
Influence of the Metal Oxide

$$\Delta G = \Delta H - T\Delta S$$
$$dQ_{rev} = \mathrm{T}\, dS$$



Two stage Process
Influence of low (partial) Pressure

$$\Delta G = \Delta H - T\Delta S$$
$$dQ_{rev} = \mathrm{T}\, dS$$



Two stage Process
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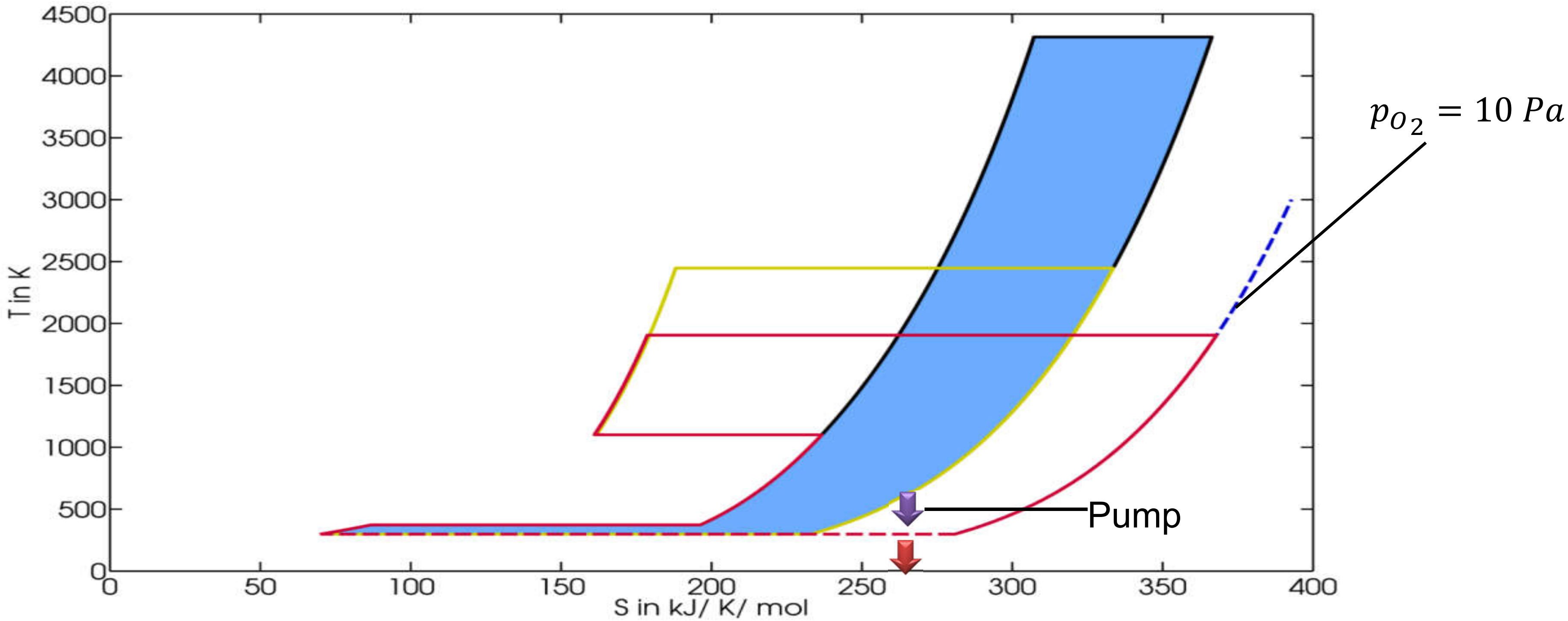

Two stage Process
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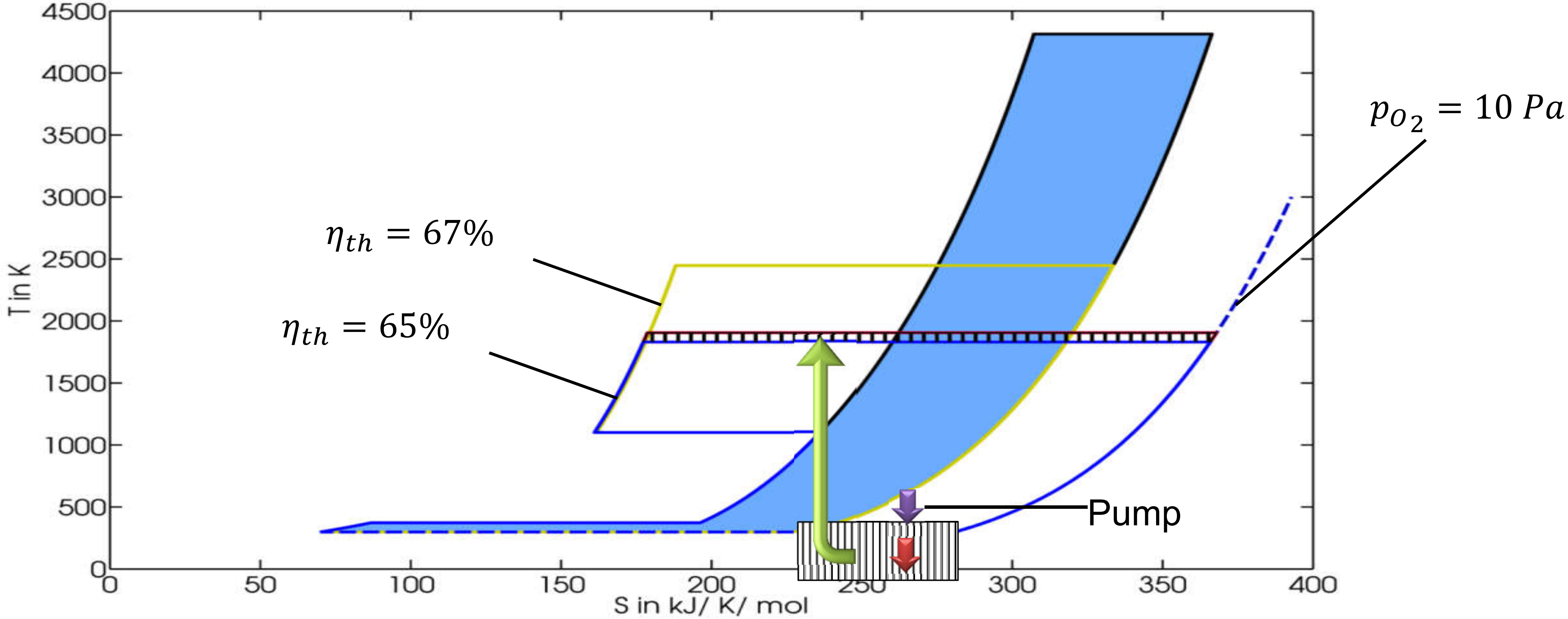
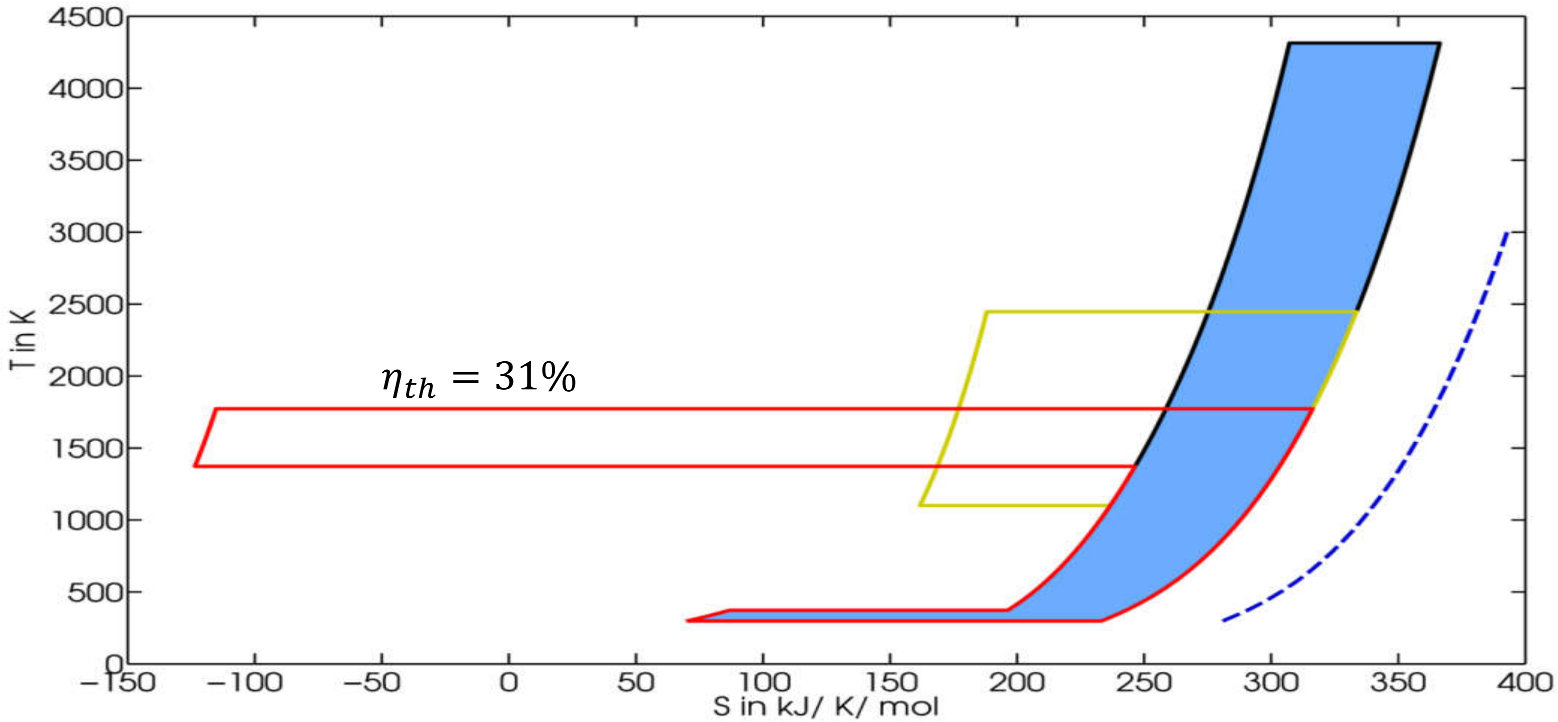


Two stage Process Temperature level

$$\Delta G = \Delta H - T\Delta S$$

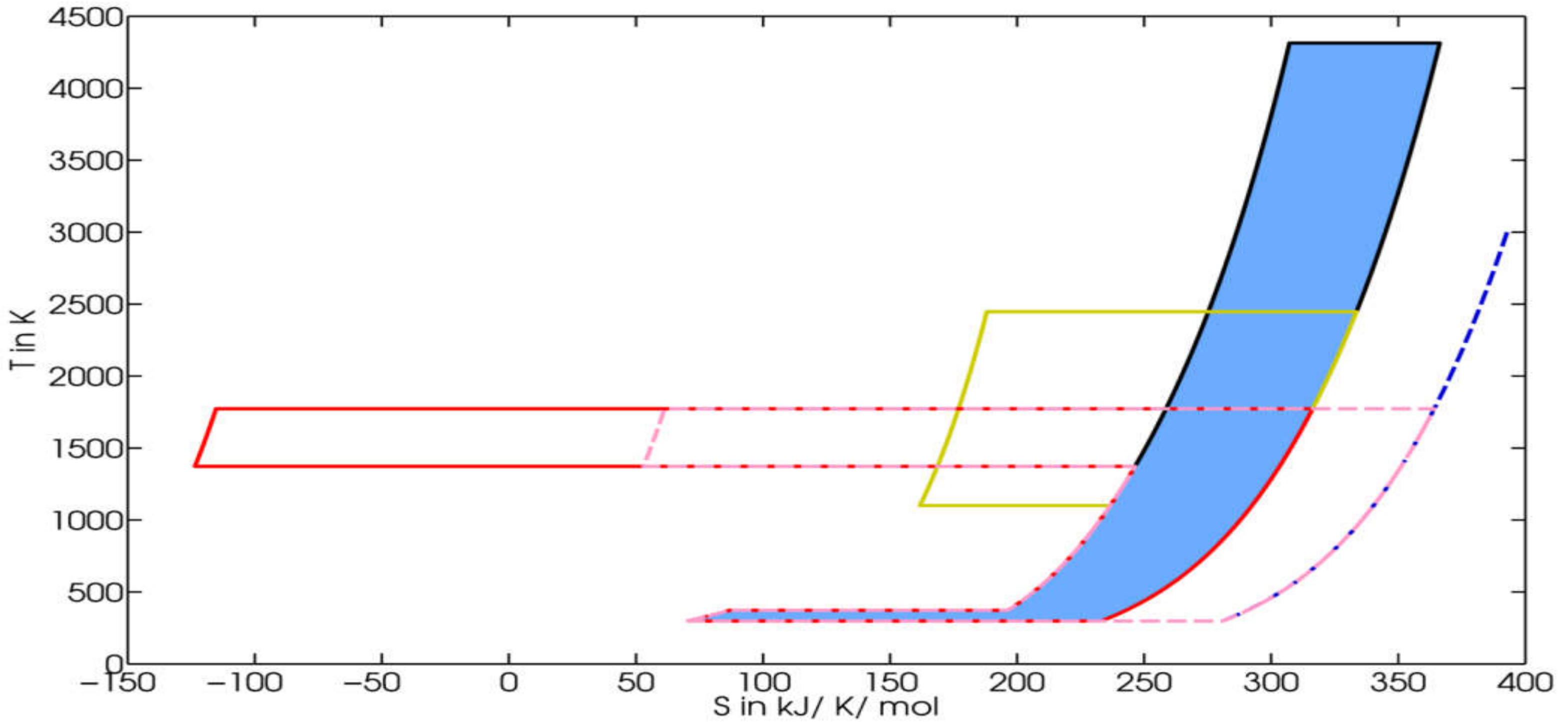
$$dQ_{rev} = \mathrm{T}\ dS$$



Two stage Process Temperature level

$$\Delta G = \Delta H - T\Delta S$$

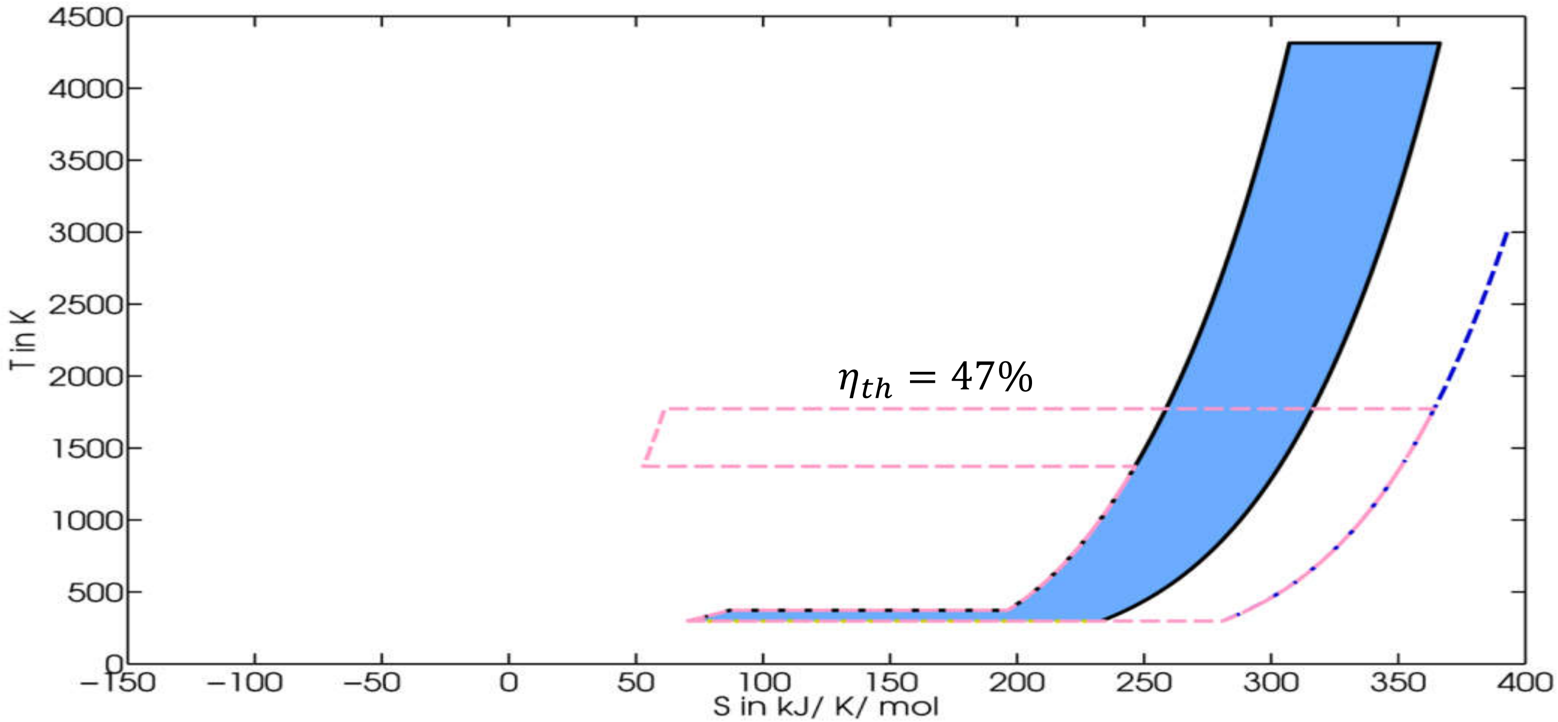
$$dQ_{rev} = \mathrm{T}\ dS$$



Two stage Process Temperature level

$$\Delta G = \Delta H - T\Delta S$$

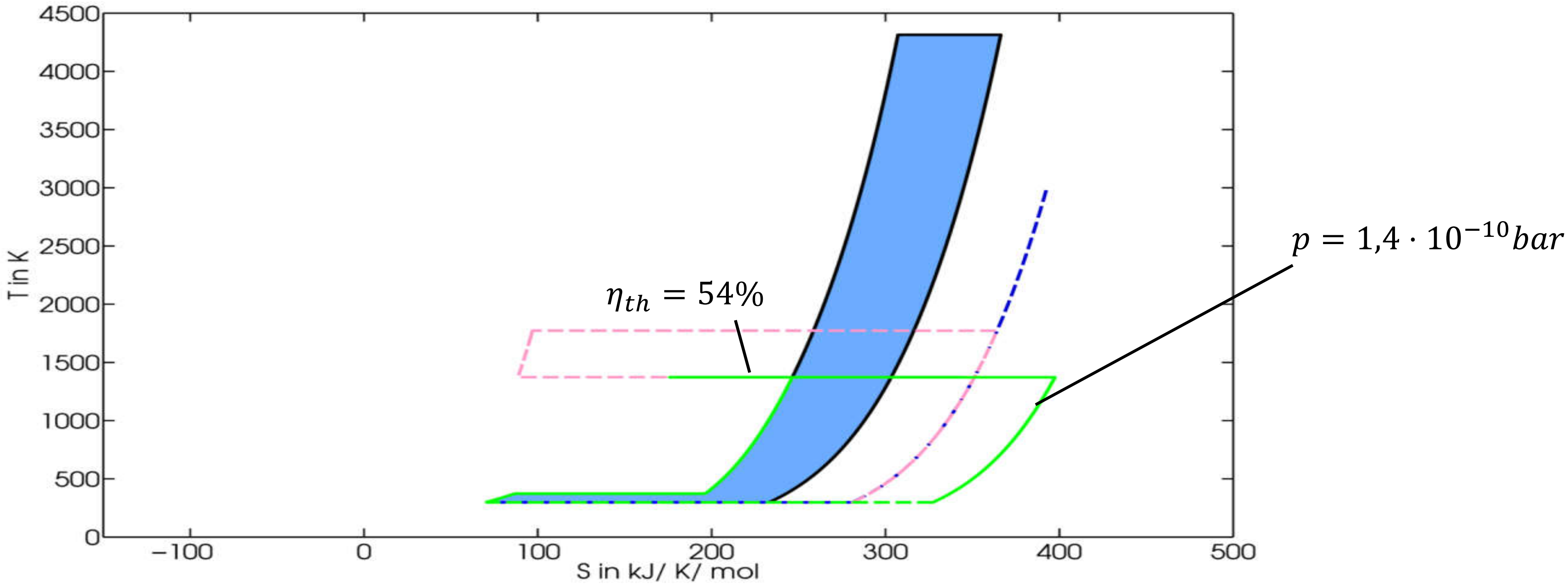
$$dQ_{rev} = \mathrm{T}\ dS$$



Two stage Process Reduction and Oxidation at the same Temperature Level?

$$\Delta G = \Delta H - T\Delta S$$

$$dQ_{rev} = \mathrm{T}\, dS$$



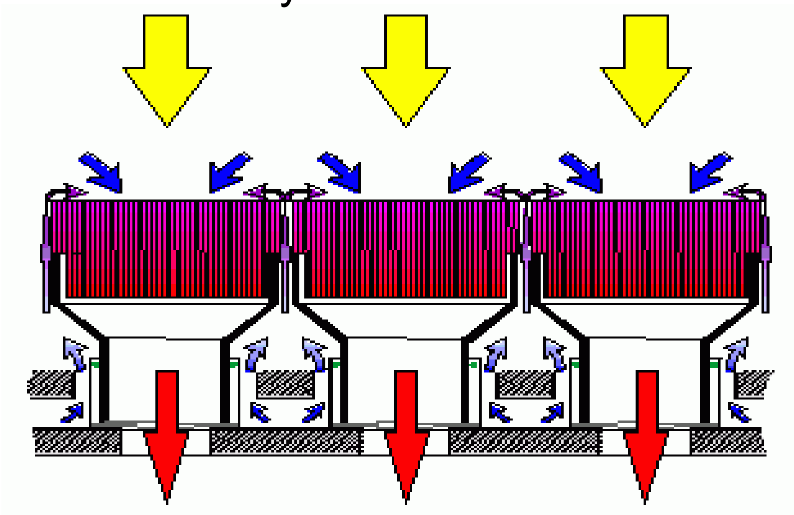
If the pumping power is generated bei solar energy (η = 15%), the efficiency drops to 30 %

The HYDROSOL Idea

2001, Almería, Spain – Discussion between APTL and DLR

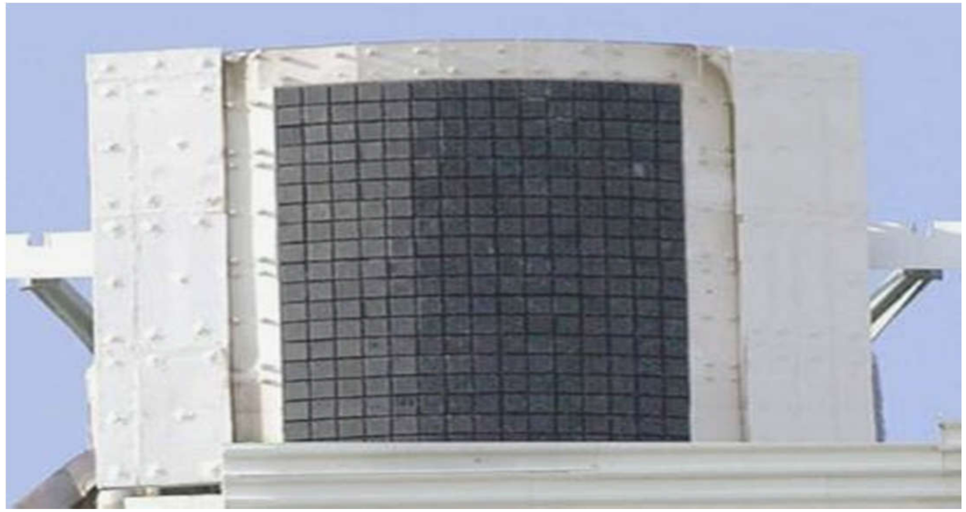
Open Volumetric Solar Receiver Design: High Temperature Air Receiver (HiTRec)

Volumetric receiver concept
SiSiC monoliths with
Honey comb structure



Hot Air 760 – 1000°C

- PSA Demonstration:
  Power: 3 MW_{th}

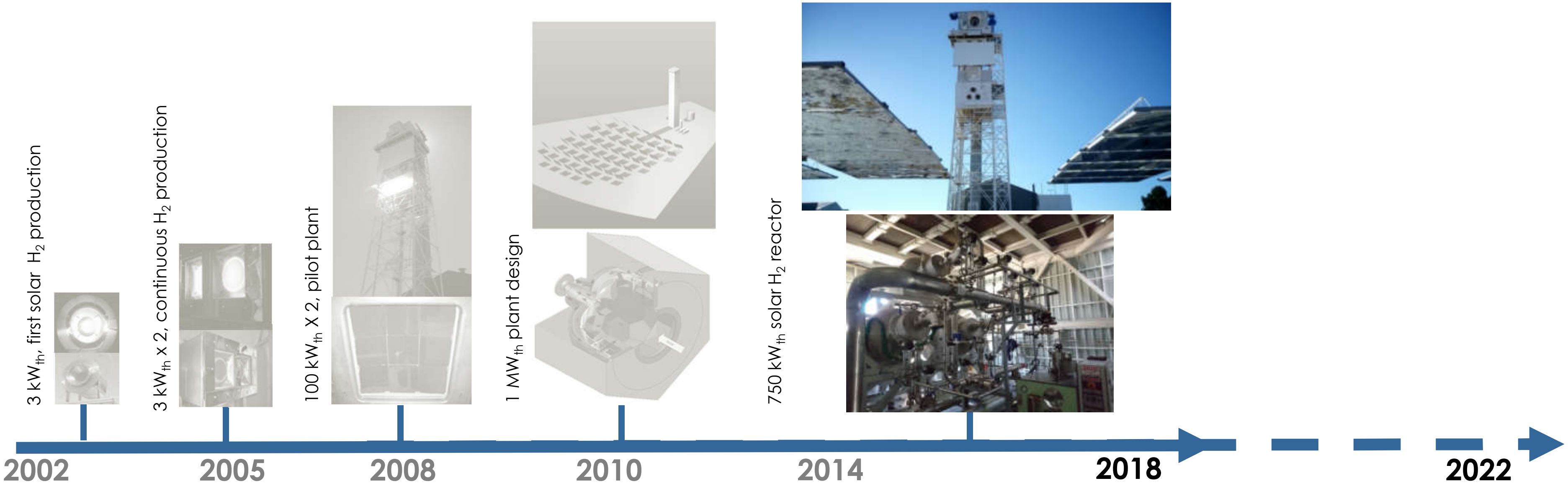


- Irradiation > 750 kW/m^2
- Long term test at PSA

Result: HYDROSOL Project - STREP EU FP 5 (Nov. 2002 – Oct. 2005)

HYDROSOL – 20 years development

HYDROSOL HYDROSOL-II HYDROSOL-3D **HYDROSOL-PLANT**



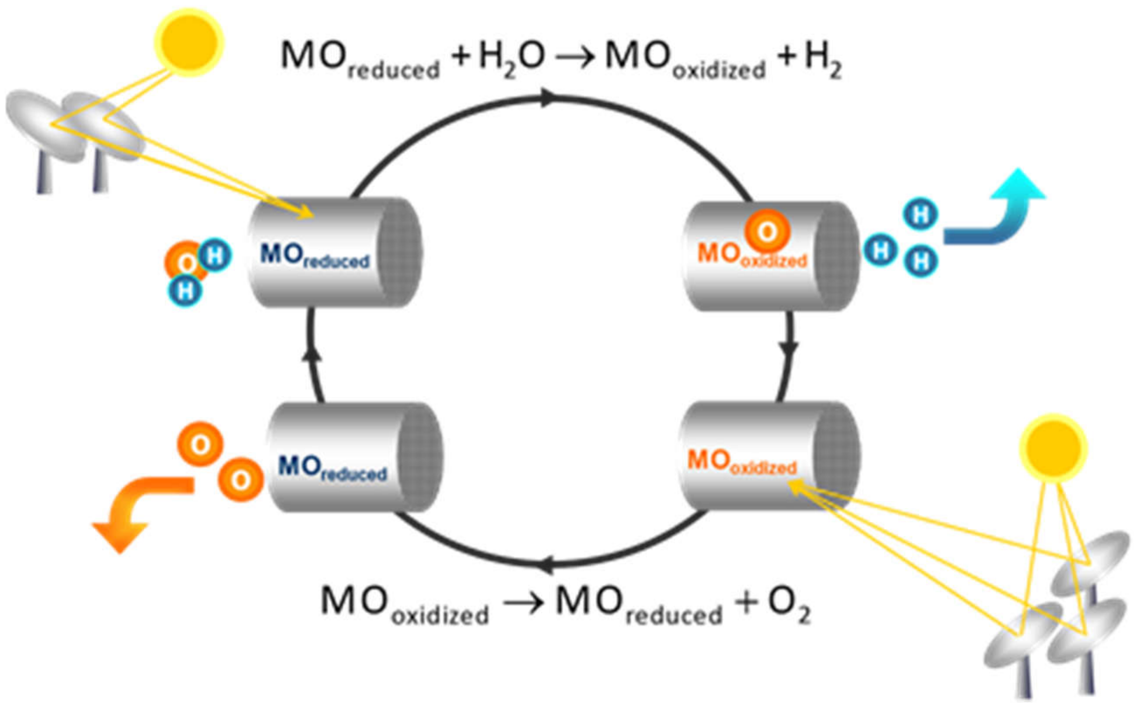
APTL/CERTH
DLR
JM
STOBBE

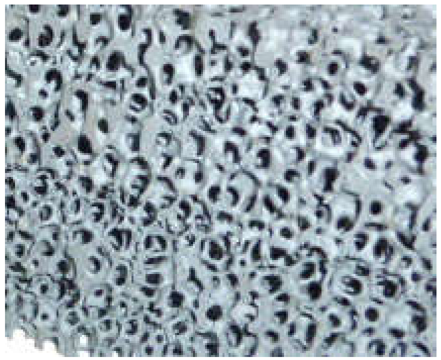
APTL/CERTH
DLR
CIEMAT
STOBBE

APTL/CERTH
DLR
CIEMAT
HYGEAR
TOTAL

APTL/CERTH
DLR
CIEMAT
HYGEAR
HELPE

HYDROSOL-PLANT at a glance





- 3 kg H_2 production/week
- Nickel ferrite and Ceria foams as REDOX-mat.
- 1400°/1100° regeneration temperature
- advanced heat recovery
- steam overheating
- hydrogen separation and compression

Results: Impressions from the plant

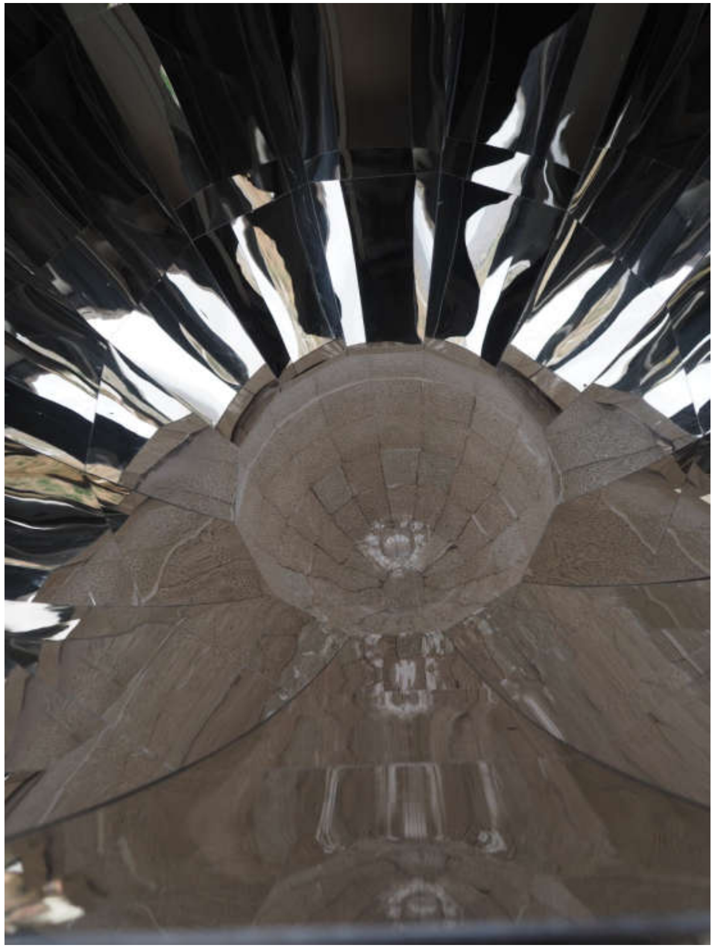
Results: Impressions from the plant




Results: Impressions from the plant




Results: Impressions from the plant



HYDROSOL – 20 years development

HYDROSOL

3 kW_{th}, first solar H_2 production

2002

APTL/CERTH
DLR
JM
STOBBE

3 kW_{th} x 2, continuous H_2 production

2005

HYDROSOL-II

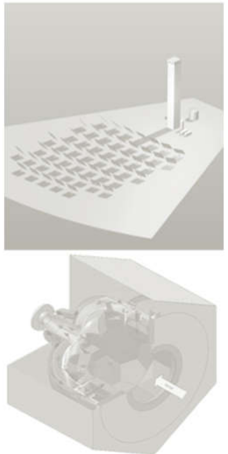
100 kW_{th} X 2, pilot plant

2008

APTL/CERTH
DLR
CIEMAT
STOBBE

HYDROSOL-3D

1 MW_{th} plant design

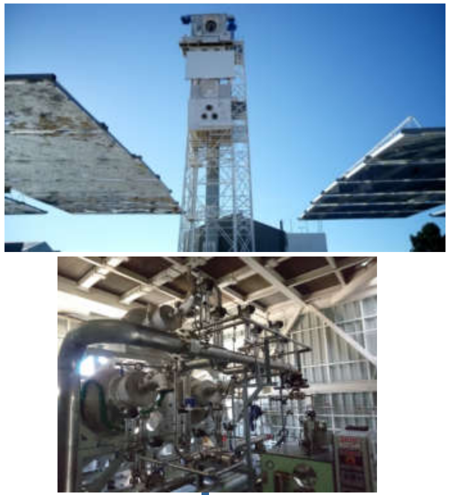


2010

APTL/CERTH
DLR
CIEMAT
HYGEAR
TOTAL

HYDROSOL-PLANT

750 kW_{th} solar H_2 reactor



2014

2018

APTL/CERTH
DLR
CIEMAT
HYGEAR
HELPE

HYDROSOL-beyond

- Improvement of heat recovery
- 5% efficiency of the 750 kW plant
- > 1000 cycles

2022

APTL/CERTH
DLR
CIEMAT
HYGEAR
ENGICER
SUPSI
CEA
ABENGOA

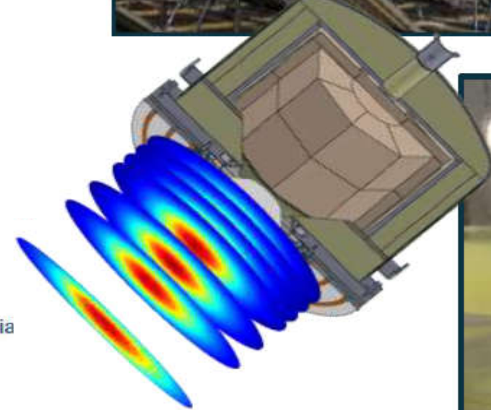
DLR

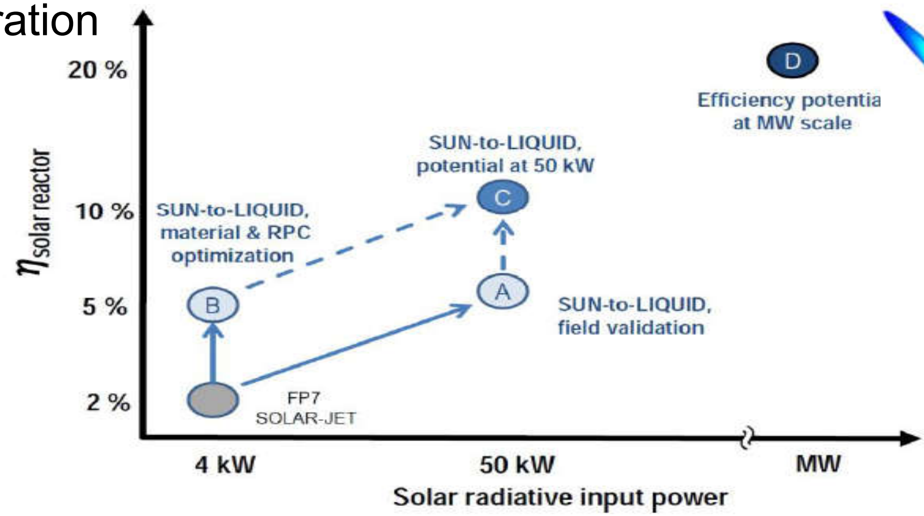
SUNlight-to-LIQUID: Integrated solar thermochemical synthesis of liquid hydrocarbon fuels

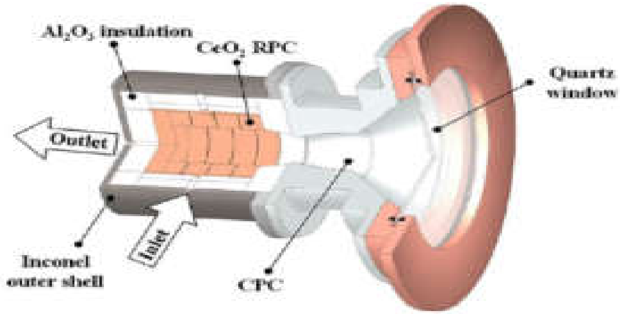
Aim
- Demonstration of ceria redox cycle for liquid hydrocarbon production at at 50kW scale
- Follow up of EU Solar-Jet

Main Tasks
- Techno-economic analysis
- Design and construction
- Experimental demonstration
- Optimization (Thermal & Material)
- Plant modeling

Partner
- Bauhausluftfahrt, ETH, DLR (SF/VT), IMDEA, HyGear, Abengoa Research, ARTTIC

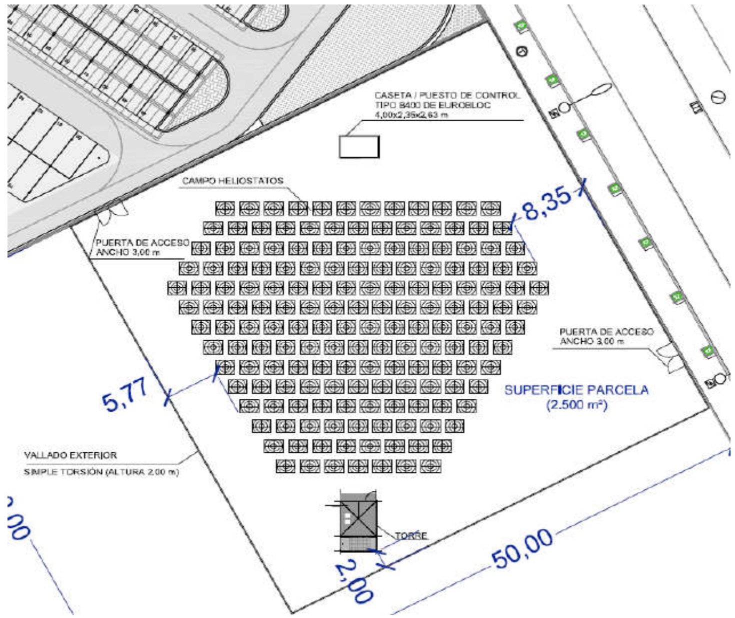






Solar field and tower at IMDEA – Mostoles, Madrid

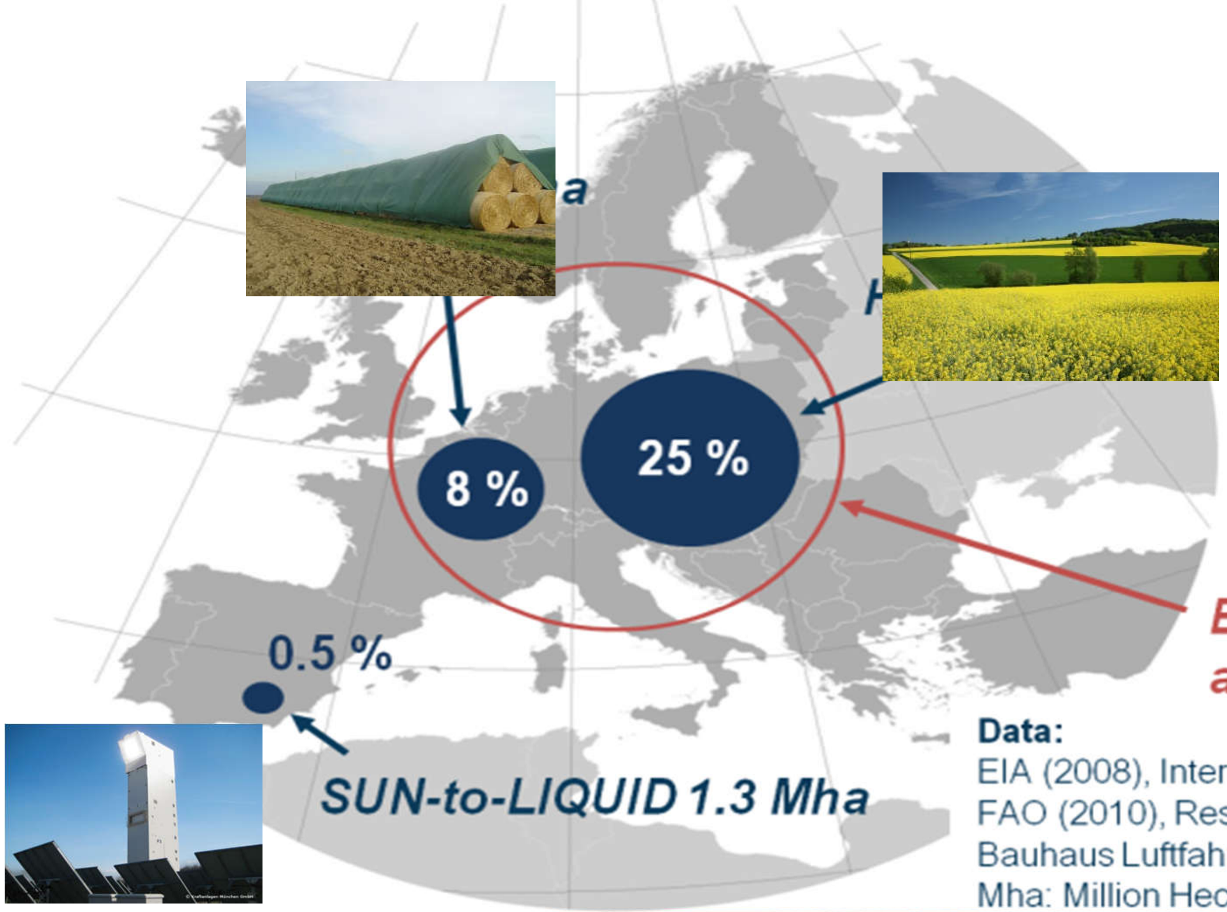
Successful Construction of tower and field
50kW aperture (d=16cm);
C_{mean}=2500 (peak 4000);
169 Heliostats;



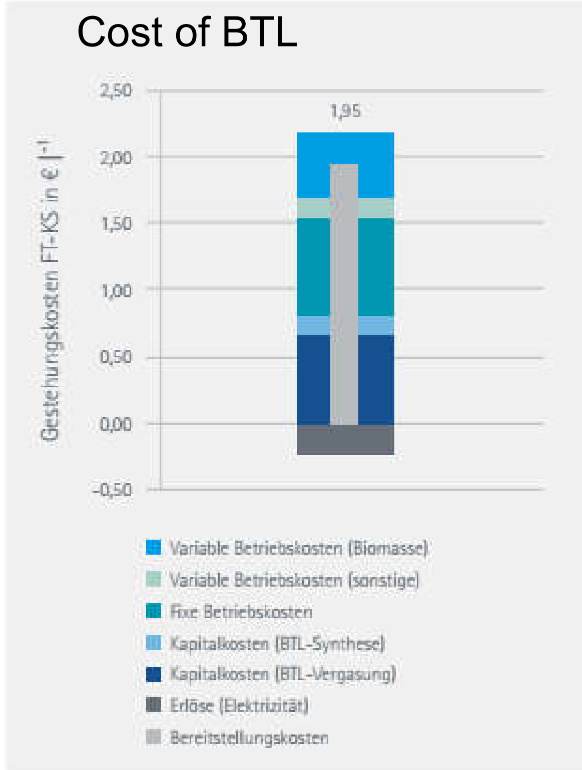
SUN-TO-LIQUID DEMONSTRATION EVENT on June 13, 2019 in Móstoles, Spain

https://www.sun-to-liquid.eu/page/post/sun-to-liquid-demonstration-event-on-june-13-201913.php

Fraction of E27 agricultural surface to provide European Kerosin demand of 2005:



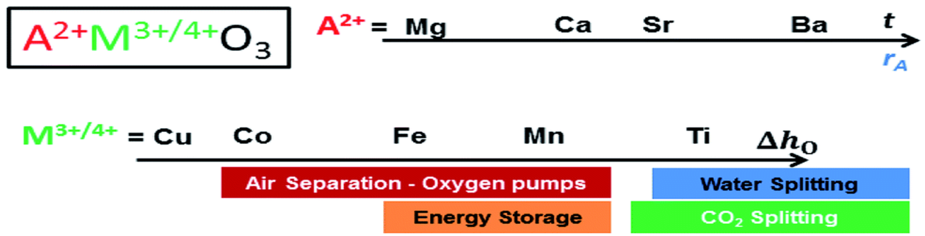
European agricultural area 245 Mha



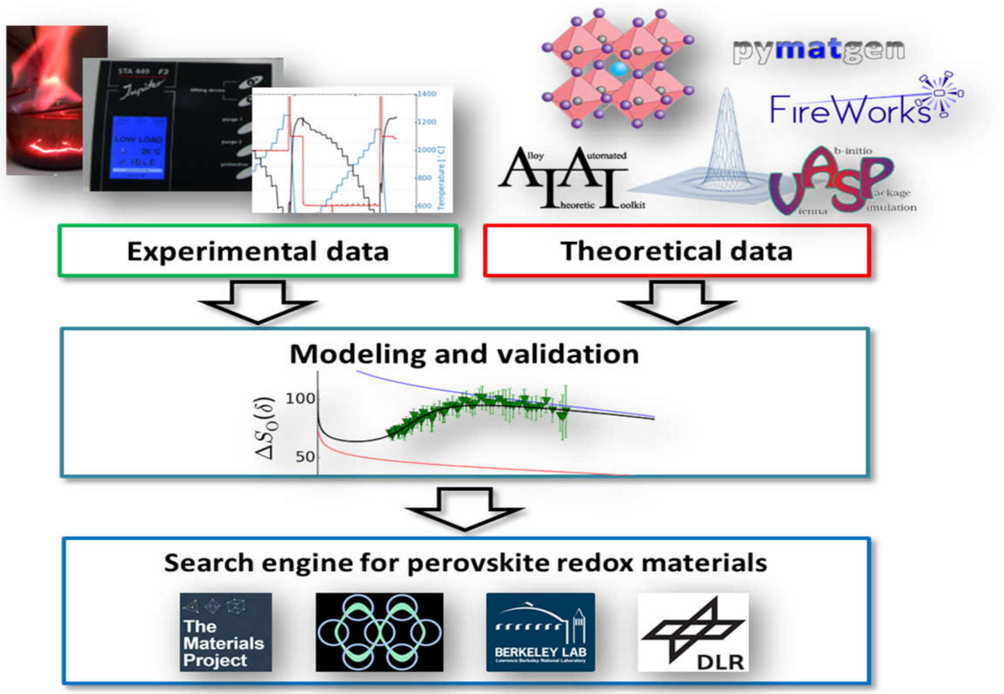
Data:
EIA (2008), International Energy Annual 2006
FAO (2010), ResourceSTAT-Land 2005
Bauhaus Luftfahrt Inventory of Energy Crops
Mha: Million Hectare

Perovskite screening

- Solid solutions of perovskites for different applications



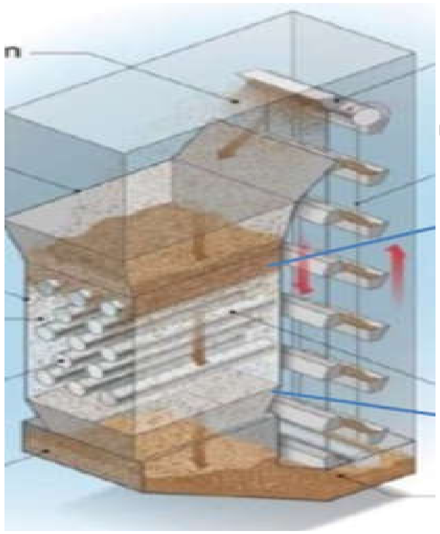
- Redox thermodynamics studied experimentally via the van‘t Hoff method
- Collaboration with Lawrence Berkeley National Laboratory, USA for modelling of experimental data and generation of additional theoretical data (DFT)
- modelling of heat capacity using DFT results



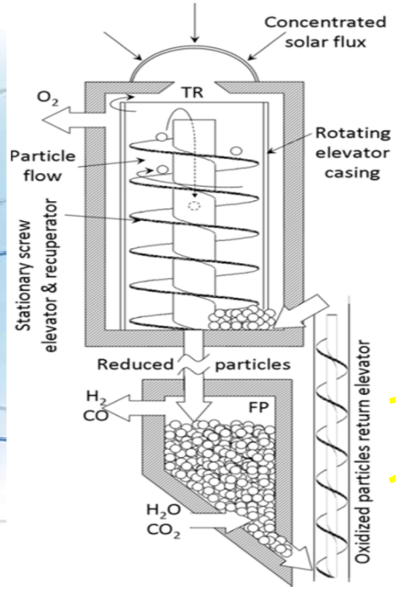
Particlereceiver – Overcomes Heat Transfer Limitations

- More homogenous irradiation of the absorption materials
- Better heat transfer by particle movement
- Continuous operation
- No limitation for the amount of material in the receiver
- Easy replacement of spent materials
- Particle movement and heat transfer needs to be understood

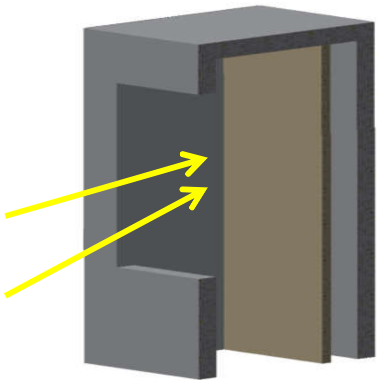
DLR



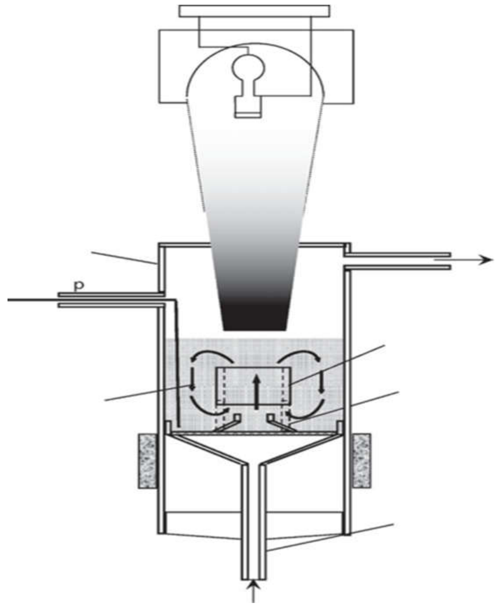
J. Martinek and Z. Ma



Sandia

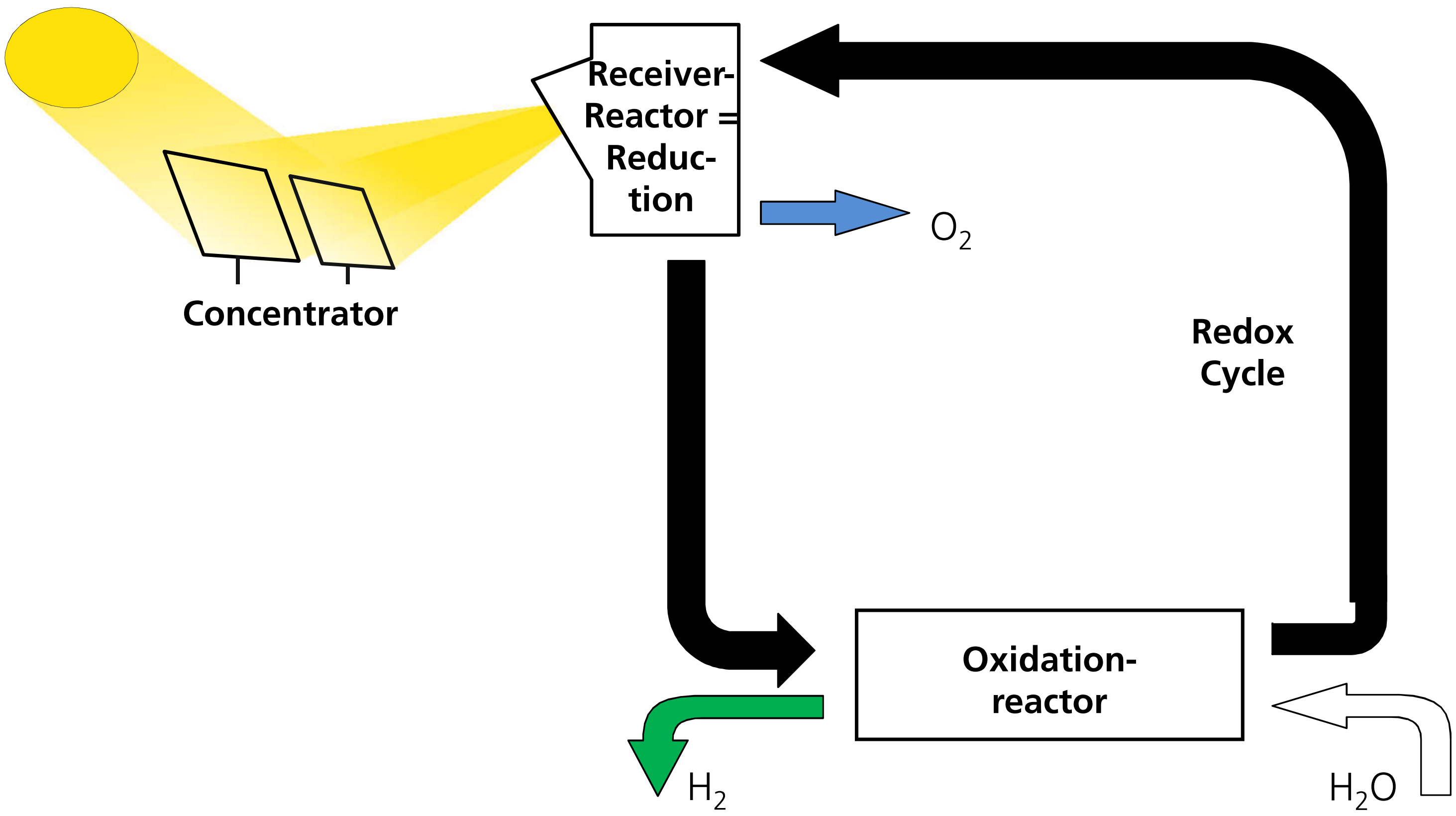


Sandia, DLR



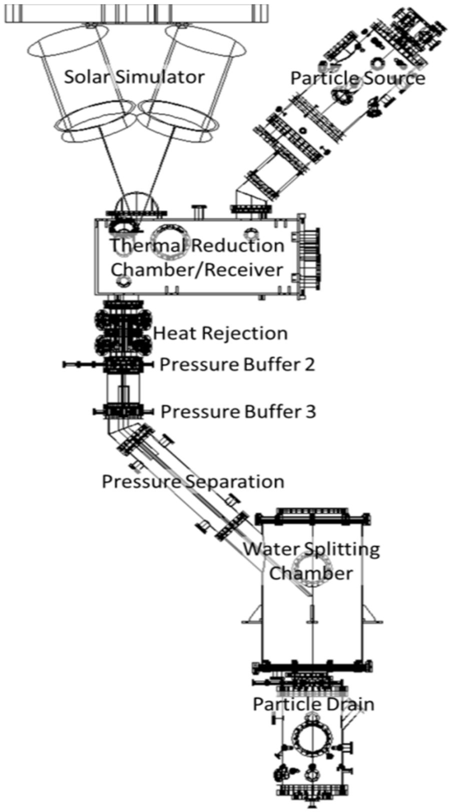
Niigata Univ.

Direct Concept – Overcomes Heat Transfer Limitations



STCH - Plant

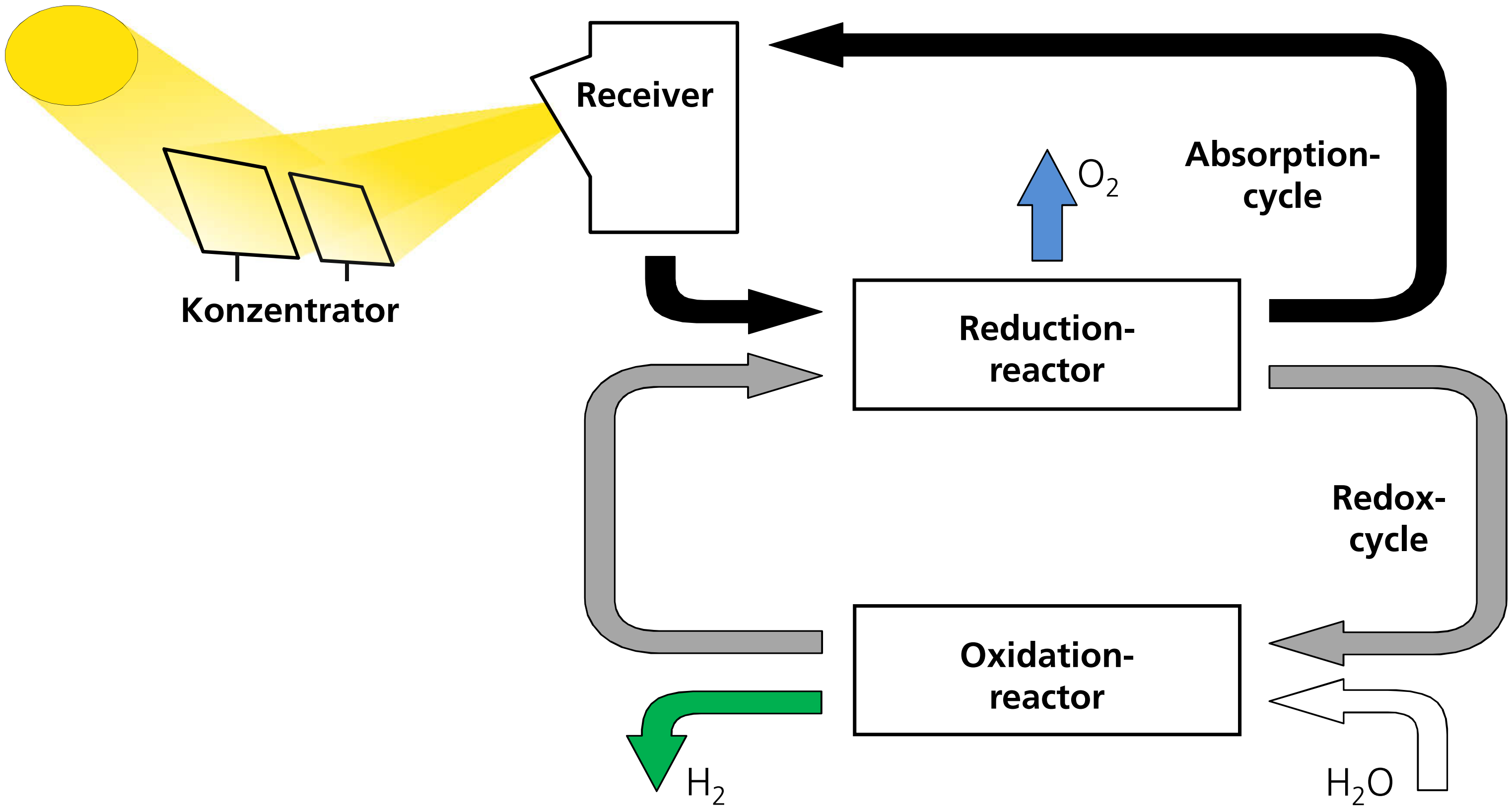
DLR + Sandia Reactor assembly and testing underway at Sandia National Laboratoties, Albuquerque, NM, USA



Hot particles falling from receiver

Particles: As received, heated, reoxidized

Indirect concept – Solves the reaction rate problem

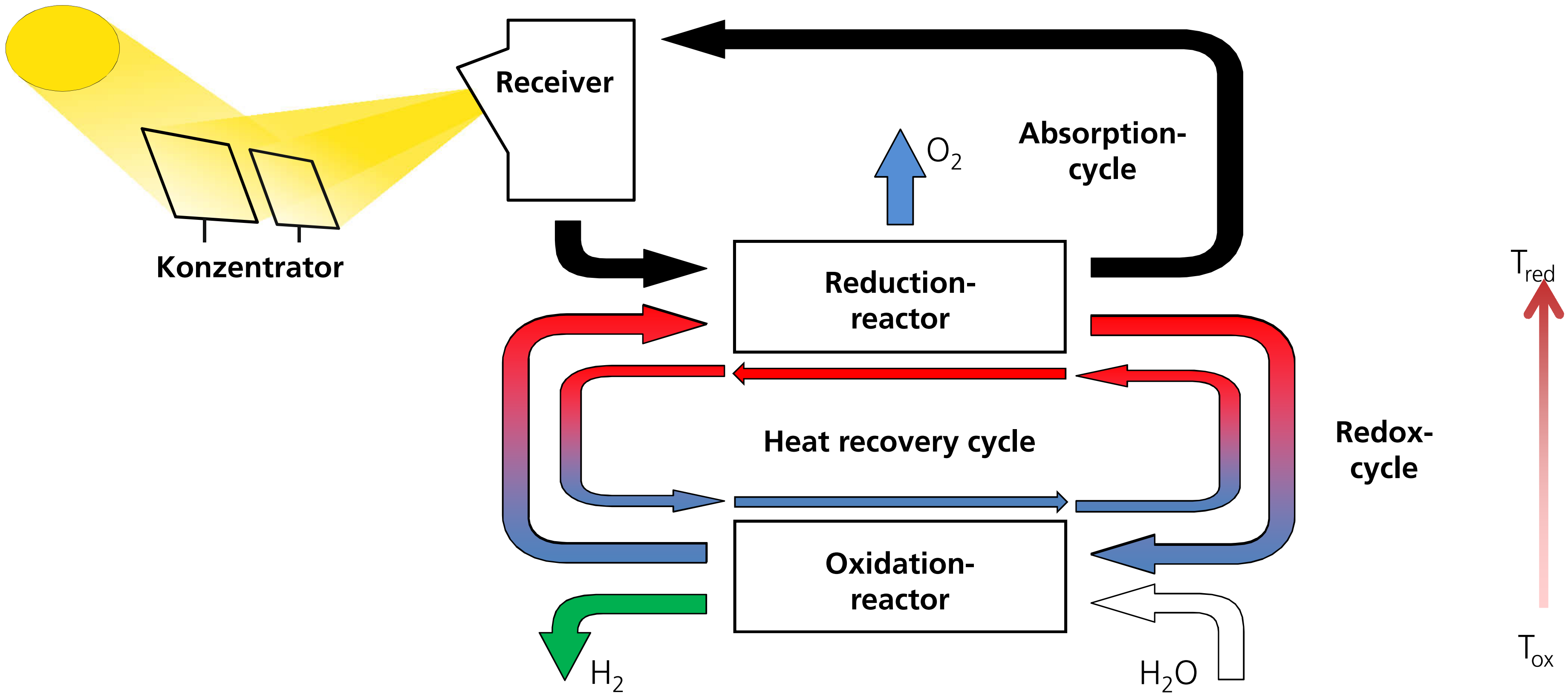


Decoupling of the different steps

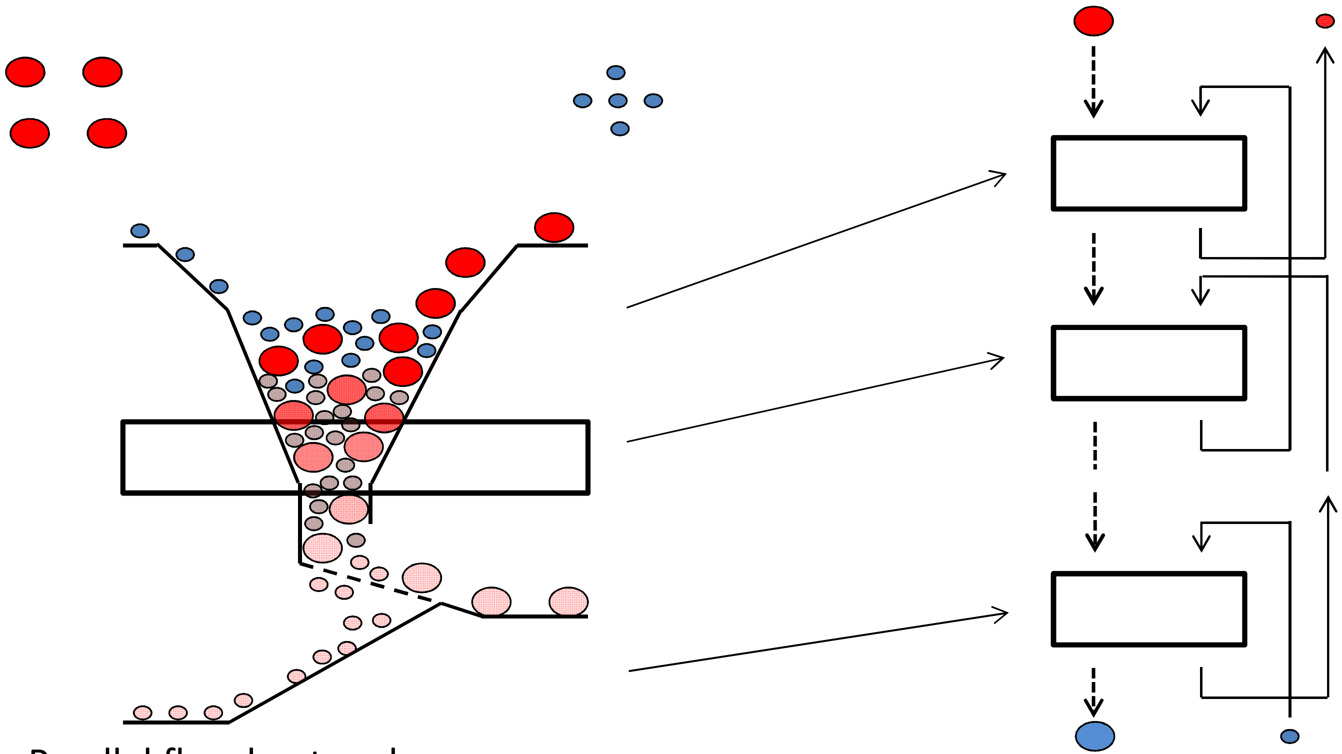
Het transfer materials:
- Inert gases
- Liquid metals
- Solid particles

Brendelberger and Sattler, Solar Energy 2015

Particle Mixing Heat Recovery

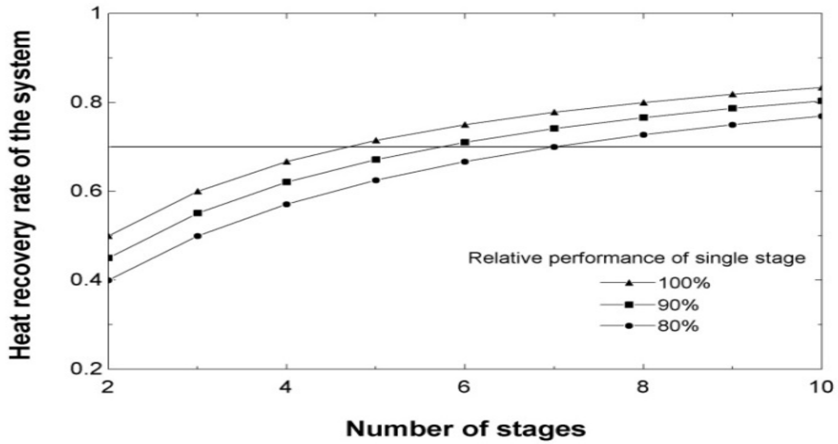


Particle – Particle Heat Transfer



Parallel flow heat exchanger

Quasi counter flow-heat recovery system



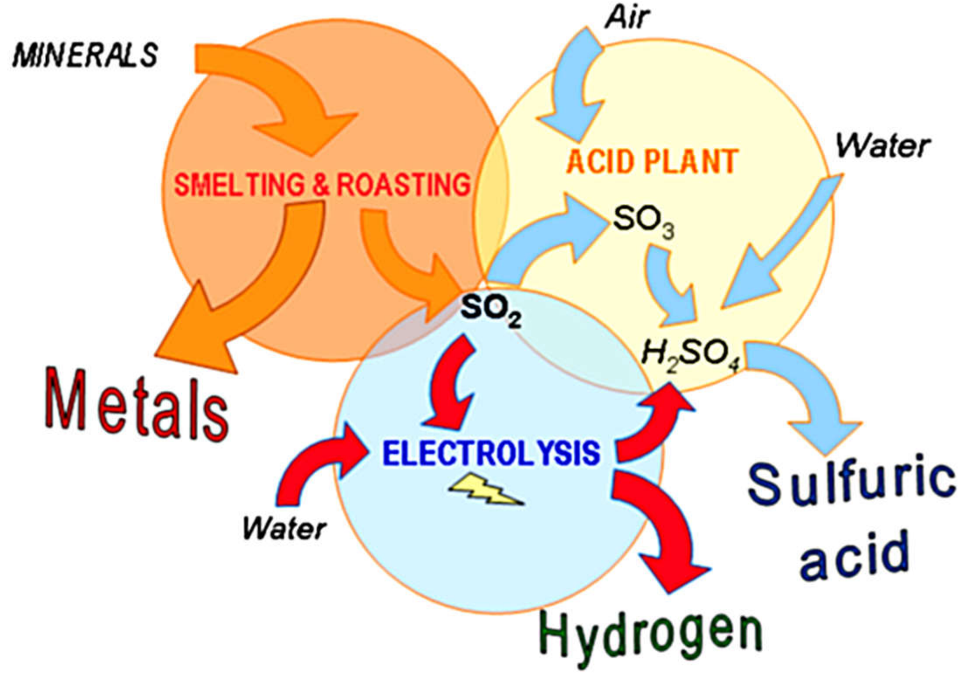
Felinks et al., ATE 2014
Brendelberger et al., ASME 2014

Source: J. Felinks

SOL2HY2
Solar To Hydrogen Hybrid Cycles

- FCH JU project on the solar driven Utilization of waste SO_2 from fossil sources for co-production of hydrogen and sulphuric acid
- Hybridization by usage of renewable energy for electrolysis
- Partners: EngineSoft (IT), Aalto University (FI), DLR (DE), ENEA (IT), Outotec (FI), Erbicol (CH), Oy Woikoski (FI)
- >100 kW demonstration plant on the solar tower in Jülich, Germany in 2015

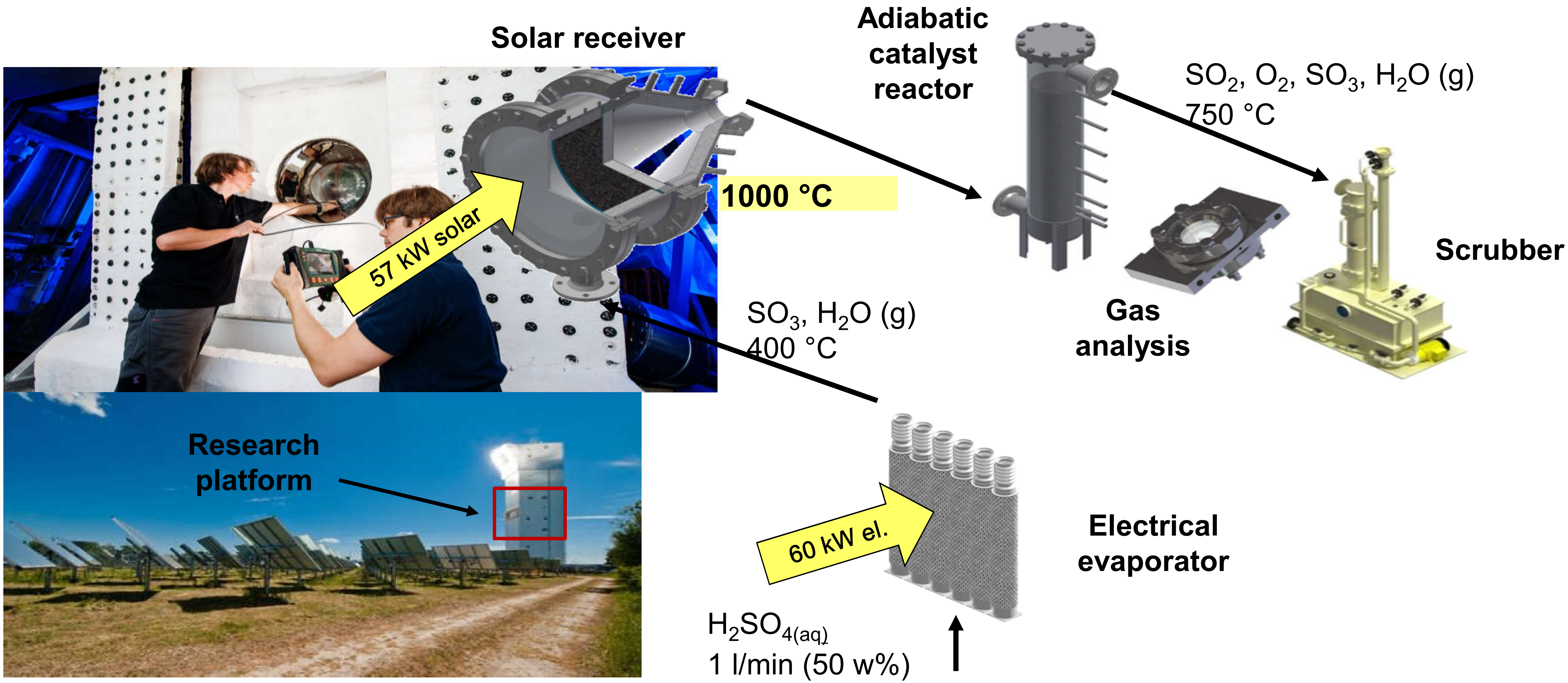
Outotec™ Open Cycle (OOC)



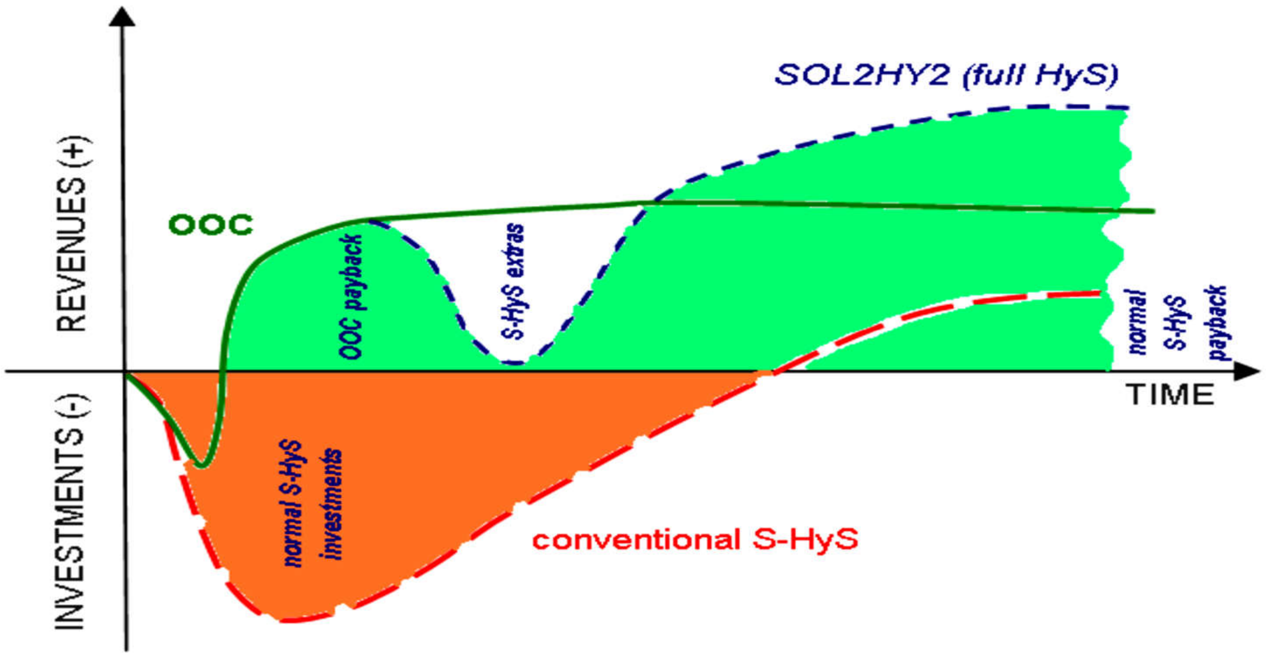
- Utilization of waste SO_2 from fossil sources
- Co-production of hydrogen and sulphuric acid
- Hybridization by renewable energy for electrolysis

https://sol2hy2.eurocoord.com

Design of SOL2HY2 pilot plant



Investments vs. revenues



- Reduction of initial investments
- Financing of HyS development by payback of OOC
- Increase of total revenues

Co-funded by the Horizon 2020 Framework
Programme of the European Union

PEGASUS

Renewable **P**ow**e**r **G**eneration by Solar P**a**rticle Receiver Driven **Su**lphur **S**torage Cycle

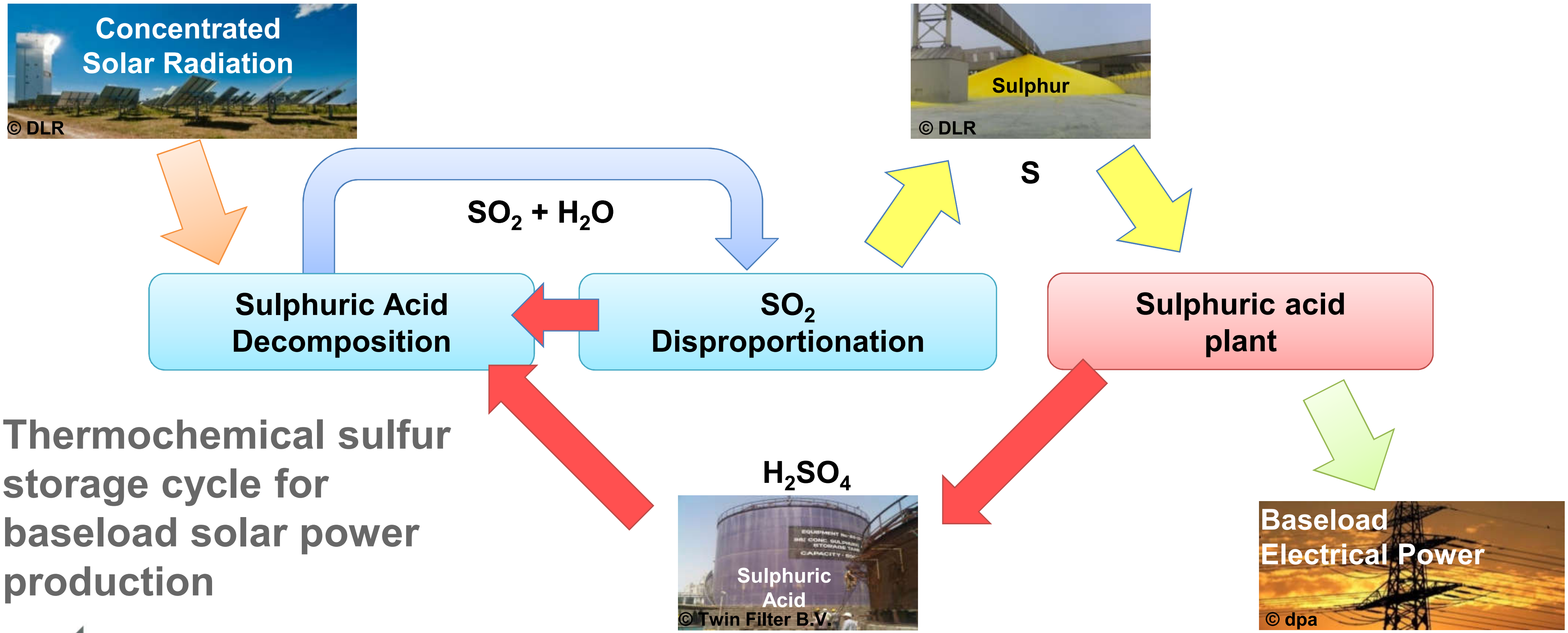
- **Aim**
  - Sulphur-based cycle for **baseload** solar power production
  - Development and demonstration of key components
  - Component modelling, process simulation, techno-economics

- **Tasks**
  - Catalytic particles development, manufacturing
  - Centrifugal particle solar receiver adaptation, operation
  - Design, construction, off-sun operation of particle reactors for sulphuric acid splitting
  - Development, construction and operation of sulphur burner
  - Process simulation, techno-economics, integrated solar operation

- **Partners**
  - Germany: **DLR** (Coordinator), **KIT**
  - Greece: **APTL/CERTH**
  - Poland: **Baltic Ceramics**
  - Italy: **Processi Innovativi**
  - Israel: **BrightSource**

PEGASUS

Renewable **P**ow**e**r **G**eneration by Solar P**a**rticle Receiver Driven **Su**lphur **S**torage Cycle

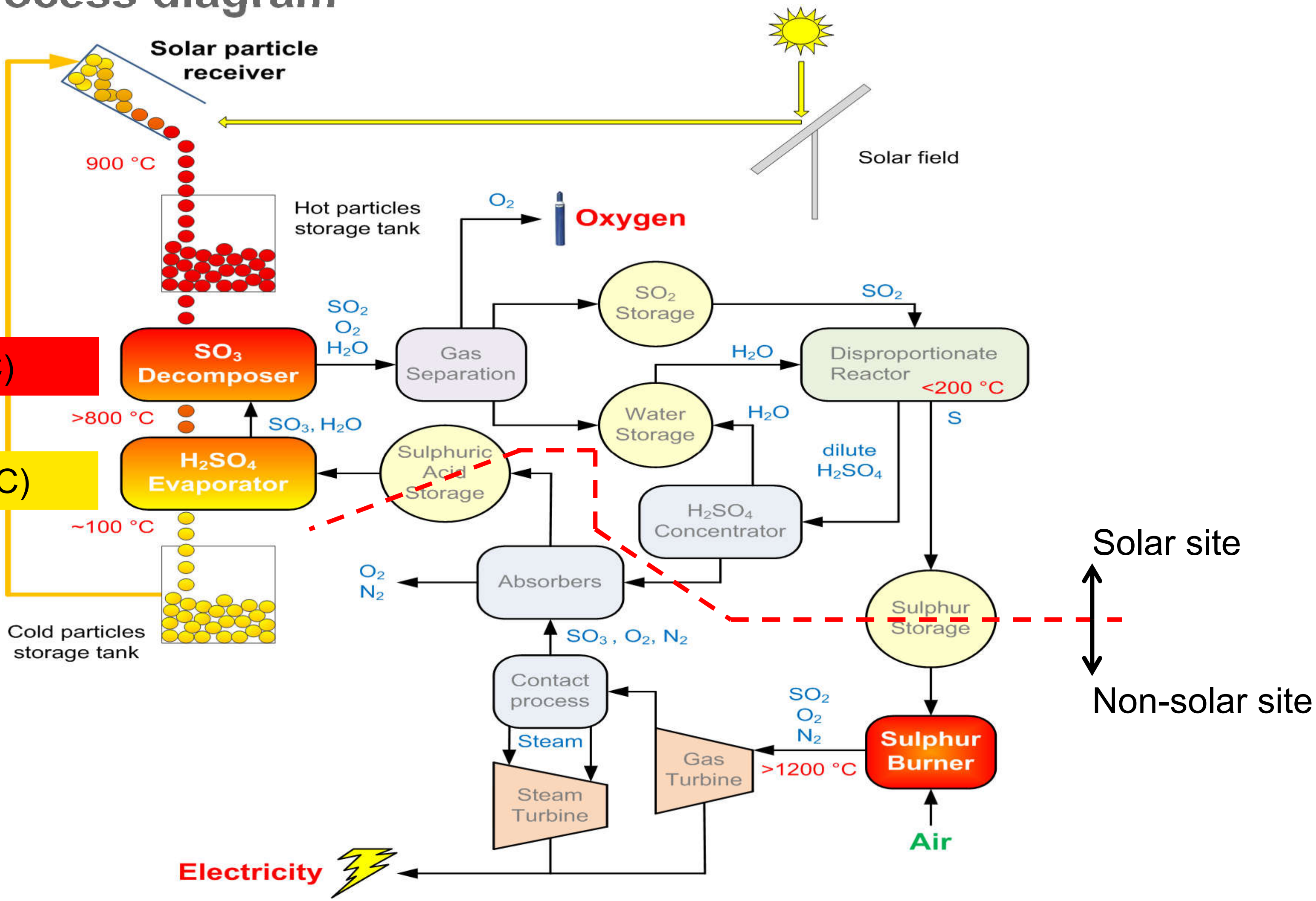


Thermochemical sulfur storage cycle for baseload solar power production

PEGASUS – Process diagram

$SO_3 \Rightarrow SO_2 + ½ O_2$ (850°C)

$H_2SO_4 \Rightarrow SO_3 + H_2O$ (400°C)



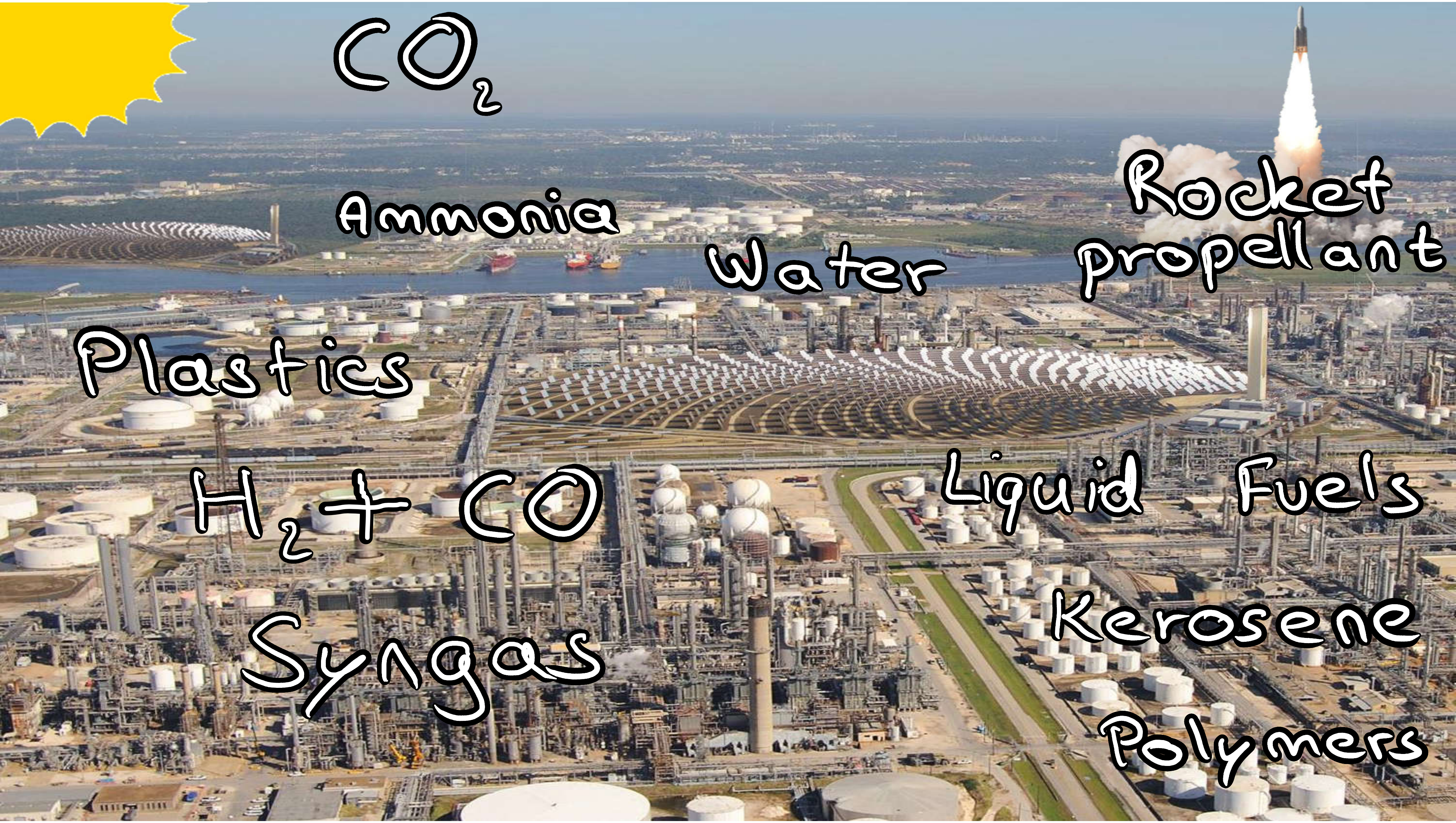
Centrifugal particle solar receiver optimization

Application of pilot receiver developed in CentRec project

- Centrifugal particle receiver was erected on scaffold in front of Juelich Solar Tower
    - Nominal power: 2.5 MW_{th}
    - Diameter of the aperture: 1.13 m
    - Max. particle temperature: 1000 °C
- Commissioning completed
- Solar testing of CentRec started in autumn 2017

Project PEGASUS

- Solar testing of particles in CentRec pilot was carried out in 2018
- Pre-testing of catalytic particles is underway (i.e. absorptance, pouring angle, flow angle, thermo-shock, crushing resistance, abrasiveness, emissivity)
- 3 tons of catalytic particles will be produced, and tested probably in 2021
    - The reason is that DLR just builds a second tower next to the existing one as the facility is completely booked for years


CO_2
Ammonia
Water
Rocket propellant
Plastics
$H_2 + CO$
Syngas
Liquid Fuels
Kerosene
Polymers